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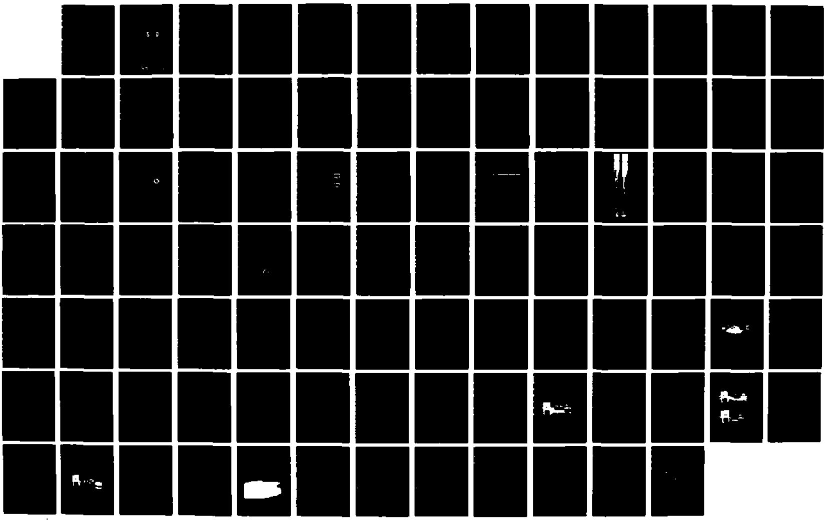

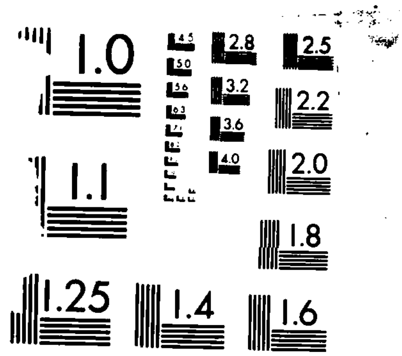

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ELECTROMAGNETIC INSPECTION OF WIRE ROPES USING SENSOR ARRAYS

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ELECTROMAGNETIC INSPECTION OF WIRE ROPES USING SENSOR ARRAYS

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ELECTROMAGNETIC INSPECTION OF WIRE ROPES USING SENSOR ARRAYS

ABSTRACT

The work reported in this report was conducted by NDT Technologies, Inc. for the Office of Naval Research under Contract N00014-83-C-0484.

The Program Objective was to develop a technique and apparatus for a reliable inspection of wire ropes in service. In particular, the objective was to develop advanced methods and apparatus for an accurate quantitative in-service identification and characterization of wire rope defects using electromagnetic NDE methods.

The progress achieved by this research can be summarized as follows:

- A line of electromagnetic instruments was developed. These instruments can reliably test wire ropes in service, and they can remedy the shortcomings of previous wire rope inspection methods.
- The new instruments allow a quantitative determination of loss of metallic cross-sectional area (LMA) caused by localized flaws (e.g., broken wires) and by distributed flaws (e.g., corrosion or abrasion) with a quantitative resolution of 50 mm. (Here, "quantitative resolution" is defined as the required minimum flaw length for which the sensor provides a quantitative measure of LMA directly, without additional signal processing).
- The qualitative identification of flaws shorter than 50 mm is possible without further signal processing.
- To gain a better understanding of the instrument performance, we undertook an experimental and theoretical investigation of the magnetic flux patterns inside the instrument and wire rope.
- Using an IBM Personal Computer in combination with appropriate interface hardware, we implemented computer-aided defect identification methods.
- Using these computer aided quantitative defect identification methods, the quantitative resolution can be further improved to approximately 10 mm. For shorter flaws, a slightly less accurate estimate of LMA is still available.
- As compared to previous state-of-the-art instruments, the quantitative resolution of the new instruments was improved from approximately 500 mm to 50 mm, a factor of 10.
- As compared to the previous air coils, the use of sense coils with ferrous cores gives an improved signal-to-noise ratio and signal repeatability.
- We developed an accurate optical rope position/velocity transducer system which is primarily used for interfacing our rope inspection system with the data acquisition digital computer.

- In addition, for field use, we developed a rugged magnetic rope position/velocity transducer system, with a resolution of approximately 1" or less.

- We implemented methods and prototype instrumentation for the inspection of wire rope end sections, close to the rope terminations.

1. INTRODUCTION

A recent statistical analysis of over 8000 laboratory and field test records [1] revealed some interesting facts on the condition of wire ropes in service:

- Approximately 10% of all ropes considered showed a strength loss of over 15%; more than 2% of the ropes had lost over 30% of their nominal strength. In other words, while still in service, 10% of all ropes were in an unacceptable and potentially hazardous condition, and 2% of the ropes were in an extremely dangerous condition.
- Conversely, more than 70% of all ropes in the sample were removed from service with little or no strength loss.
- The above findings suggest that only a very small percentage of all ropes was replaced in a timely fashion.

These observations vividly illustrate the unreliability of the prevalent wire rope inspection methods, especially of visual wire rope inspections: Although the majority of all ropes are retired prematurely, as a precaution, many ropes in service are severely degraded and in a dangerous condition. Because visual inspections are unreliable, many users replace wire rope at fixed intervals, usually based on some ton-mileage figure.

Present visual inspection methods have serious deficiencies:

- They do not guarantee wire rope safety, because they simply cannot reliably identify unsafe wire ropes which should be replaced.
- They are wasteful, because they usually cannot identify wire ropes that have additional service life left.

Because failure of wire ropes inevitably causes a serious hazard, safety codes and authorities mandate periodic inspections. As an example, the US Code of Federal Regulations (30 CFR 811) deals with wire rope safety in the mining industry. Similar regulations apply to all other areas of wire rope usage. The Safety Code for Elevators (ANSI A17.1) including the Elevator Inspectors Manual (ANSI A17.2), and the Safety Code for Overhead and Gantry Cranes (ANSI B30.2.0) provide but a few additional examples of safety codes dealing with wire rope safety. These regulations concisely summarize present wire rope inspection methods and the major causes of wire rope failure.

All safety codes give specific criteria for the replacement of wire rope. Obviously, test procedures should be able to determine whether or not these replacement criteria apply. All inspection procedures, especially the predominant visual inspection method, are deficient in this respect.

A word about government certification of nondestructive test instruments: Only the Canadian government requires approval of rope inspection equipment. Neither the US government nor any other government, worldwide, requires or grants instrument certification.

The principal deterioration modes of wire rope can be categorized as follows:

Loss of Metallic Cross-Sectional Area (LMA):

(i) Abrasion (external)
caused by rubbing along floor or other surfaces

Abrasion (internal)
caused by nicking, high pressures, poor lubrication

(ii) Corrosion (external,internal)
caused by environmental conditions, poor lubrication

Localized Faults (LF):

(iii) Broken Wires
caused by fatigue, plastic wear, martensitic embrittlement, mechanical damage

(iv) Kinks and other Mechanical Damage

Although many nondestructive test procedures, employing radiation and optical, acoustical and mechanical methods, have been proposed and tried in the past, at the present time, only visual and electromagnetic test methods are practical.

In this report, we first describe the previous state of the art in wire rope inspection procedures and nondestructive inspection instrumentation. Then we describe, in detail, a new type of wire rope test equipment and inspection procedures which were developed by NDT Technologies,Inc. with support from the US Navy, Office of Naval Research under Contract N00014-83-C-0484.

2. WIRE ROPE INSPECTION: PRIOR STATE OF THE ART

2.1. Visual Inspection

The most obvious and the simplest, but not the easiest, method of testing a rope for flaws is by visual inspection. The two basic types of visual inspection procedures are

(i) the "Rag-and-Visual" Method and

(ii) Rope Diameter Measurements.

Both procedures are discussed in the following.

The rag-and-visual method is useful for the detection of broken wires. This obvious method always supplements any other test procedure. Traditionally, a wire rope is inspected for broken wires in the following manner: The inspector is stationed next to the rope and grasps it with a rag or gloves. Broken wires will often porcupine and, as the rope moves at inspection speed, catch the rag or glove. The rope is then stopped at that point and the inspector tries to ascertain the rope condition by a visual examination. This procedure is satisfactory for non-preformed rope, where broken wires porcupine.

Since most wire rope is preformed, a different and more tedious test procedure must usually be applied: the rope is moved two or three feet at a time and visually examined at each stop. For a thorough inspection strong lights, mirrors, a magnifying glass and rope cleaning compound are frequently used in addition to rags. Because of the limited attention span of the examiner, and because the rope is often covered with grease, the reliability of this cumbersome and time consuming method leaves a great deal to be desired.

The visual-and-rag method, time consuming and unreliable as it is, is adequate for the detection of broken surface wires in cases where life is not imperiled by failure to detect a few broken wires, and where distributed defects, such as internal and/or external abrasion and corrosion, are not a problem. An elevator cab, for example, is supported by four to eight wire ropes, each with a considerable margin of safety. Furthermore, many elevators operate in a well-protected environment, where corrosion is not a problem. Because the rag-and-visual method usually cannot detect internal flaws, elevator ropes have fiber cores to prevent internal rope damage. Therefore, visual rope inspection for elevators which operate in a well-protected environment can be considered adequate.

On the other hand, visual inspection methods, even for elevators in well protected environments, are unnecessarily time consuming and, therefore, expensive. Since some wire ropes are not easily accessible, the examiner has to operate in strenuous and awkward positions, sometimes for long periods of time. Furthermore, because the inspector is in close proximity and in direct contact with the moving wire rope, the visual-and-rag method is potentially hazardous. Numerous serious accidents during rag-and-visual inspections have occurred in the past.

Another visual inspection method is the measurement of the rope diameter with a caliper. This procedure is useful for the detection of loss of metallic cross-sectional area. Evaluations of rope diameter measurements are based on a comparison of the original diameter - when new and subjected to a known load - with the current reading under like circumstances. A marked reduction of rope diameter indicates degradation. A change of rope diameter can indicate external and internal rope damages, such as excessive external abrasion, internal and external corrosion, loosening or tightening of rope lay, and broken cores. Unfortunately, these damages often do not cause a change in rope diameter, making this method, at best, questionable.

Rope diameter measurements are often unreliable, cumbersome and not easy to evaluate. An example: Most standards require that rope is to be removed if the outer wire wear exceeds one-third of the original diameter of the outer wires. Wire wear is not easy to determine by visual methods, so discovery relies upon the experience of the inspector. Another example: Internal corrosion, a very serious type of rope degradation, most often occurs with no external evidence which could be detected by the visual-and-rag method and/or diameter measurements.

In mining, aerial tramway and chairlift applications, rope failure usually has serious and fatal consequences. Inspection solely by visual methods for these ropes must be considered inadequate and can only be justified if no other alternatives are available. As a consequence of the unreliability of the presently predominant visual inspection methods, wire rope is often replaced prematurely, in an attempt to maintain a sufficient safety margin.

In summary, visual rope inspection can be characterized as follows:

Advantages

- Very simple: it does not require expensive instrumentation.
- It is adequately reliable for non-critical applications with high safety margins, and where internal rope degradation is not a problem.
- Despite its many deficiencies, it is an important inspection method which should supplement any other test procedure.

Disadvantages

- Because of their inherent difficulty and unreliability, visual rope inspections require a trained and experienced inspector.
- Only surface flaws can be detected. The inspector cannot detect internal flaws such as internal corrosion or abrasion. If the rope is covered with lubricating grease or plastic sealing materials, inspection is impossible.
- Inspections are not sufficiently reliable for life sustaining applications with low safety margins. Reliability depends on the attention span, the judgment and the experience of the inspector.

- If only visual inspection methods are used, premature rope retirement is often necessary, but not sufficient, to maintain an adequate safety margin.

- Inspection is time consuming, cumbersome, expensive, and potentially dangerous for the examiner.

- An objective record of the rope inspection is not available.

2.2. Electromagnetic Wire Rope Inspection

Electromagnetic methods for nondestructive testing of wire ropes are more reliable than purely visual methods. While they should not completely replace careful visual inspections, nondestructive inspections provide great insight into the condition of a rope. Because of its reliability, especially if supplemented by visual inspections, nondestructive testing has gradually become an accepted method for the inspection of wire ropes in the mining industry, for ski lifts, and for other applications in North America, Europe, and South Africa.

Two different and distinct types of nondestructive inspection methods have evolved:
(i) Localized Fault Inspection (LF Inspection), and

(ii) Inspection for Loss of Metallic Cross-Sectional Area (LMA Inspection).

Similar to the rag-and-visual method, LF inspection is suitable only for the qualitative detection of localized flaws such as broken wires or corrosion pitting. Therefore, the small hand-held LF instruments produced by one manufacturer a few years ago have been called "electronic rags" [2], [3].

The LMA inspection method is suited for the detection and quantitative evaluation of distributed flaws such as abrasion and corrosion. Much more reliable and convenient than visual diameter checks, LMA inspection can replace diameter measurements made with a caliper. Therefore, LMA instruments could be called "electronic calipers." The more advanced of the presently available instruments allow a simultaneous LMA and LF inspection.

All of the present rope inspection instruments are hinged and can be easily mounted on the rope in the field. Except in the most extreme conditions, inspection of any installed rope is possible. One of the available instruments, the LMA-75 from NDT Technologies, Inc., which was developed under the present contract, can even inspect tightly spaced elevator ropes. Some instruments are operated by rechargeable batteries, which makes their operation very convenient even under adverse field conditions.

To perform an inspection, the inspector places the instrument on the rope. While the rope travels through the instrument, a strip chart recorder and/or a cassette tape recorder records the test signals. Using audio-visual signals such as buzzers, headphones, or

indicator lights, the inspector, assisted by the test instrument, can also inspect the rope visually. He can then compare visible flaws with the recorded chart patterns. Most instruments come with an electro-mechanical distance counter, which makes it easy to correlate the actual flaw position on the rope with the chart recording.

A program of regularly scheduled nondestructive inspections, typically at four to six month intervals, is of particular value for safe and extended rope usage. Periodic inspections allow a more accurate assessment of the rope condition than a mere single inspection. To establish baseline data for the subsequent inspections, this program should be initiated by an electromagnetic inspection of the new rope after its installation and after a sufficient break-in period. Since an accurate and objective record of the rope condition is available for each inspection, it is possible to compare rope data at the time of each inspection. A complete documentation of a rope's gradual deterioration, throughout its entire service life, is therefore available. The end of safe service life is usually reached when the rope degradation exceeds certain limits and/or when the degradation rapidly accelerates between inspections. Furthermore, periodic inspections can prevent premature rope deterioration by making the operator aware of faulty operating conditions such as worn or misaligned sheaves.

While the operation of most instruments requires considerable skill, some instruments are easy to operate even for moderately skilled personnel. Chart recordings are simple to interpret, and this can be done on site. For comprehensive evaluation, a cassette tape recording can be produced which is returned to the lab, where a thorough computer-aided analysis is performed. Successive inspection results are compared with data from previous inspections.

Inspections by electromagnetic methods are safer, faster, more convenient and, in many cases, less expensive than visual inspections. Since the instrument can be attached to the rope, the inspector does not need to be in physical contact with the rope, making inspections safer and more convenient. Time savings of approximately 80% as compared to visual inspections, with associated savings in man-hours, have been reported [3].

In summary, electromagnetic wire rope inspection can be characterized as follows:

Advantages

- Under all conditions, it is much more reliable than purely visual inspections.
- A permanent and objective record of the rope condition is readily available.
- External and internal defects can be detected.
- Since nondestructive rope inspections are very reliable, rope life can usually be safely extended. Premature rope replacement can be

avoided, while at the same time wire rope safety is improved.

- Electromagnetic inspection is much more convenient, less time consuming, and less dangerous for the inspector than purely visual methods.

Disadvantage

- Suitable instrumentation and a trained operator are required.

Presently available wire rope inspection instruments are discussed, categorized and critically compared in the following.

2.2.1. Performance Criteria

To compare the performance of different instruments, we first define and discuss the following performance criteria. These criteria can serve as an objective and quantitative performance measure and can make the comparison of available wire rope inspection instruments more concise and rational.

1. Resolution. The Resolution of a transducer is measured as the smallest distance between flaws for which the transducer provides distinctly separate flaw indications. Resolving Power is defined as the reciprocal of resolution.

2. Quantitative Resolution. The Quantitative Resolution is the required minimum length of a uniform flaw for which the sensor provides an accurate quantitative measurement of a rope's change of metallic cross-sectional area within a predefined small error limit. Quantitative Resolving Power is defined as the reciprocal of the Quantitative Resolution.

Because all sensors have finite quantitative resolving power, minimum flaw lengths are always required for an accurate quantitative fault identification. The concept of "quantitative resolution" is important for specifying and comparing the performance of LMA type instruments.

The following example illustrates the importance of a high quantitative resolving power: Consider a (hypothetical) rope with a 10% completely uniform loss of cross-sectional area extending over a length of 2 inches. An instrument with a quantitative resolution of 2 inches can determine the exact LMA caused by this flaw. However, an instrument with a quantitative resolution of 20 inches would indicate the same fault as a 1% loss of cross-sectional area extending over a length of 20 inches - a very inaccurate indication of the true rope condition. Of course, both instruments would give a correct indication of uniform faults extending over a length of 20 inches or longer.

An analogy can illustrate the problem: The strength of a chain is determined by the strength of its weakest link, and not by the average strength of some of its links. Analogously, the strength of a rope is determined by the minimum instantaneous cross-sectional area along the rope's length, and not by some average value of the rope's cross-sectional area.

High quantitative resolving power is important. This importance becomes evident when considering typical failures of ropes which are caused by loss of metallic cross-sectional area. For instance, in many applications, high humidity causes accumulation of water inside the rope, which causes corrosion. Therefore, most of these ropes, when close to retirement, show advanced internal corrosion, often combined with internal interstrand wear. Usually, this deterioration is not visible from the outside.

Corrosion causes typical patterns of metal loss: corrosion pitting and corrosion patches. Pitting occurs in the form of very short localized losses on the surface of individual wires, while corrosion patches extend over a number of wires. Corrosion patches have a tendency to form groups with the length of individual patches in the group extending over only a few inches. Often, some of the wires within a patch are completely separated by corrosion and form clusters of broken wires. To determine a rope's metal loss and loss of strength with reasonable accuracy, high quantitative resolution, of no more than a few inches, of the test instrument is, obviously, important.

3. Penetration. The penetration of a transducer is measured by the ratio of the signal amplitude, caused by an internal flaw, to signal amplitude, caused by an identical surface flaw. This ratio is also called the Penetration Ratio. Note that the penetration ratio depends on the defect geometry.

The amplitude of flaw related pulses depends on the location of the flaw within the rope cross section (its eccentricity). The closer the flaw is to the sensor, the higher is the corresponding flaw signal amplitude. Ideally, a sensor should have a penetration ratio of one. This means, identical internal and external flaws should be indicated by equal signal amplitudes. Actual sensors always have penetration ratios less than one, which depend on the geometry of the defect.

4. Signal-to-Noise Ratio. Only test signal components which are caused by rope defects are of interest. That part of the test signal which is not caused by defects is considered noise. The signal-to-noise ratio is defined as the amplitude ratio of the defect related signal component to noise.

A steel wire rope is an arrangement of separate wires wound in a helical shape to form strands, which are then laid together in a helix to form the rope. This very intricate and nonhomogeneous arrangement of wires forms many cavities between the wires and strands, which mimic rope flaws and cause associated signals. These structure related signals will be referred to as Intrinsic Noise. The intrinsic noise causes serious problems, and it always makes test signals very noisy.

The inhomogeneous rope surface, which is very close to the sense coils, is a primary cause of the intrinsic noise signal. Since the penetration ratio is always less than one, the signal-to-noise ratio, especially for internal flaws, can become quite small. The intrinsic noise is superimposed on defect signals and can significantly distort and conceal them.

The signal-to-noise ratio of a sensor is not uniquely defined. It is a very complicated function of sensor parameters, rope structure, and defect geometry. For a convenient comparison of signal-to-noise ratios, different instruments should be used to inspect the same rope under identical test conditions. Signal-to-noise ratios can then be determined and compared by evaluating and comparing the test signals.

5. Flaw Detectability. Flaw detectability is defined as the smallest cross-sectional area change which the sensor can detect.

Note that flaw detectability is strictly a function of and intimately related to signal-to-noise ratio. A signal-to-noise ratio greater than one is required for flaw detection.

6. Sensitivity. The sensitivity of a sensor is defined as the signal amplitude caused by a predetermined flaw.

In designing rope test instruments, sensitivity usually causes no problems, as it can easily be increased by increasing the gain of the signal amplifiers.

"Sensitivity" specifications, as given by some manufacturers, are arbitrary and meaningless. Note that flaw detectability is a function of signal-to-noise ratio rather than sensitivity.

7. Repeatability. Many sensors used for rope inspection are either subdivided or otherwise not rotationally symmetric. Hence, noise as well as flaw signals depend on the angular position of the rope with respect to the sensor head, and complete repeatability of signals cannot be assured for some instruments.

8. Magnetic Interference. Since insulating materials for magnetic fields do not exist, magnetic flux is difficult to contain. All electromagnetic rope test instruments are surrounded by a magnetic leakage field. Therefore, foreign ferrous objects, such as steel beams, pipes, steel floors, or tightly spaced ropes, in the immediate vicinity of the test instrument can influence the test results. Preventing lateral movement of foreign steel objects, for instance of adjacent ropes, relative to the sense head eliminates or minimizes problems caused by interference.

9. Weight and Size. Because instruments are used in the field for on-site inspections, sensor heads have to be mounted on the rope. Consequently, the size and weight of instruments is important. The weight of the permanent magnet assembly determines the weight of the sensor head.

For optimum performance, the magnetizer has to drive the rope into magnetic saturation under all operating conditions. To reduce the weight of the sensor head, with no sacrifice of performance, advanced instruments use ultrapowerful rare-earth permanent magnets. Other instruments use less expensive and much less powerful permanent magnets made from sintered ferrite material. There is, however, a significant weight and performance trade-off for using these less expensive and less efficient ferrite magnets.

10. Operating Convenience. For on-site field inspections, the operating convenience of an instrument is very important. Since electric power is not always easily accessible, advanced instruments are battery operated. Most instruments come equipped with a rope footage counter, and other accessories include optical and acoustical flaw indicators, digital flaw counters, stripchart recorders, and cassette tape recorders.

Some other performance criteria sometimes cannot be easily pinpointed and formulated. One such criterion is that the instrument should not exhibit any unexpected and bizarre behavior. During the past few years, a number of new instruments have appeared on the market, some of them with inferior and pathological performance characteristics, probably due to a hurried design without much field testing. This has caused some disappointment. Obviously, the prospective buyer should try to identify and avoid these types of instruments. This is not easy: most LMA instruments for measuring a rope's metallic cross-sectional area were only recently developed, and even buying from a manufacturer with supposedly many years of experience does not, necessarily, protect the user from problems.

2.2.2. Previous and Present State of the Art

2.2.2.1. LF (DC) Instruments

The first practical LF instruments for the inspection of wire ropes were developed in approximately 1935. These instruments were also called "DC" instruments, because they use DC magnetization of the rope, or "leakage flux" instruments, because they measure the magnetic leakage flux surrounding the rope. The technique used in leakage flux testing, shown in Figure 1, is to magnetically saturate a section of the steel rope in the longitudinal direction by strong permanent or electric magnets. Any discontinuity in the rope, such as a broken wire, a broken core, corrosion or abrasion, distorts the magnetic flux and and causes it to leak from the rope. Sense coils or Hall generators, close to the rope, sense the leakage flux. The movement of the rope causes the leakage flux to change and to induce voltages in the sensors. The sensor voltages are suitably combined and processed to produce the test signals.

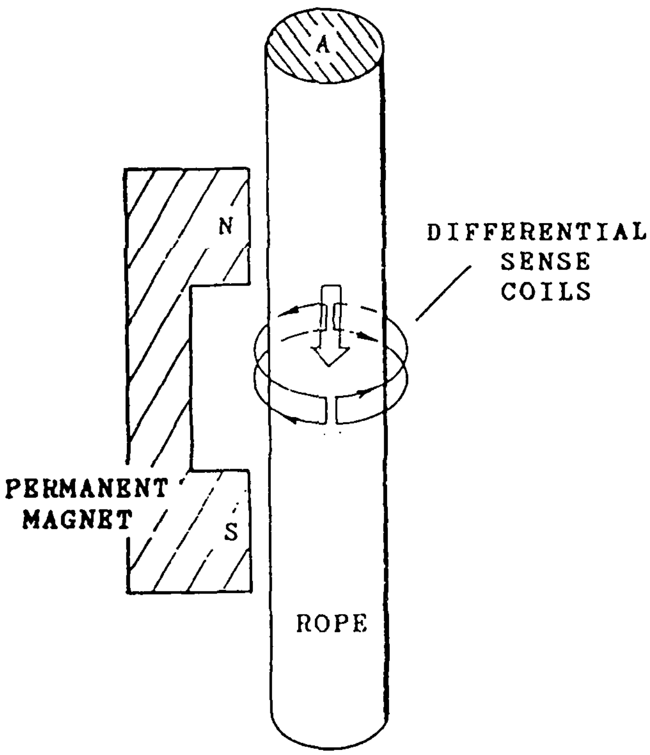


Figure 1: Leakage Flux Method with Differential Coils

Note that the sensors used for LF testing are of the differential type. This means, they can sense only changes of the magnetic flux, not the actual flux itself. Therefore, flaw detectability depends on a rapid change of the magnetic flux in the rope, which is typically caused only by broken wires or corrosion pitting. Differential sensors cannot detect and measure external and internal corrosion and abrasion, which cause a more gradual change of the magnetic flux. Hence, LF instruments are not well suited for the detection and quantitative evaluation of gradual rope deterioration caused by abrasion and corrosion. LF instruments give only a (qualitative) indication of rope flaws. A (quantitative) determination of strength loss, caused by rope deterioration, is not possible. An analogy can elucidate the problem: the height of a mountain cannot be determined with an instrument that can only measure its slope.

Quantitative signal interpretation for LF instruments is difficult, if not impossible. Therefore, an "expert" is required for signal interpretation. Since corrosion and abrasion are major causes of rope failure, instruments that can detect only localized faults must now be considered obsolete.

Nevertheless, LF inspection can detect many flaws that visual inspections cannot detect. Therefore LF testing, combined with visual inspections, is superior to any purely visual method.

Most of the present nondestructive wire rope inspection instruments on the market are of the LF type, especially in Europe and in Canada [2]-[18]. In the US, LF instruments are no longer being manufactured. LF type instruments were replaced by more advanced instruments which can, simultaneously, detect broken wires and determine the loss of metallic cross-sectional area.

2.2.3.2. LMA AC Instruments

LMA type instruments were first developed as early as 1907. These instruments were also called "AC" instruments because they use AC magnetization of the rope, as shown in Figure 2. The principles used are somewhat similar to the well-known eddy current nondestructive test method. The basic principles were implemented in a variety of ways [17], [19], [20], [21]. In these instruments, the wire rope serves as the ferrous core of a coil or a transformer. A changing rope cross section changes the impedance or mutual impedance of the test arrangement, which serves as a measure of the rope cross-sectional area.

AC testing has been practiced in North America by a Canadian company for many years. It suffers from serious deficiencies such as complicated operation, insufficient quantitative resolution, bad signal-to-noise ratio, and therefore, unreliability. A recent study [1] demonstrated the relative ineffectiveness of this method. However, as AC testing gives at least some indication of actual rope deterioration, it is not completely useless. Because of their unreliability, AC instruments will undoubtedly be replaced by other, more accurate instrumentation in the near future.

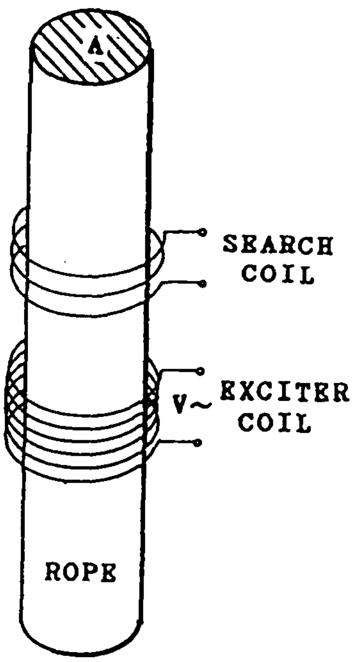


Figure 2: AC Main Flux Method

Because the first practical LMA instruments were of the AC type, all LMA type instruments are sometimes referred to as "AC" instruments by the uninitiated. "AC" is occasionally transliterated as "Area Channel" or "Area Change." This terminology adds to confusion and is a misnomer. Modern LMA instruments use DC magnetization of the rope and are obviously not AC instruments.

2.2.2.3 LMA/LF Return Flux Instruments

LMA instruments of the DC type are more accurate and reliable than AC instruments. These instruments use DC magnetization of the rope, usually by permanent magnets. When the rope is magnetically saturated, the longitudinal magnetic flux in the rope is proportional to the rope's metallic cross-sectional area. Therefore, any loss of metallic area can be determined by measuring the longitudinal magnetic flux in the rope.

The first LMA rope testers of the DC type, the Canadian Magnograph [22], [23], [24] and the British Plessey [25] instruments, developed in the late 1970s, use Hall generators to measure the magnetic flux. These pioneering instruments made a major contribution to the art of wire rope inspection. The Plessey instrument subsequently encountered patent infringement problems and is no longer commercially available. The Magnograph has overcome its early problems associated with temperature drift of the Hall generators, and its published test results [23], [24] now show it to be a reliable and rugged instrument.

The Canadian Rotescograph [26], developed in approximately 1982, emulates the Magnograph principles, with Flux Gate Sensors substituted for the Hall generators to avoid patent infringement, and with rare-earth permanent magnets replaced by less powerful ferrite magnets.

These instruments have one inherent shortcoming: To measure magnetic flux density, Hall generators and flux gate sensors have to be physically inserted directly into the magnetic flux path, in other words, the flux to be measured has to intersect the sensors. Obviously, this is impossible when measuring the flux inside a rope. Therefore, these instruments must resort to an indirect method of estimating the magnetic flux inside the rope: They measure some flux density outside the rope and derive an estimate of the longitudinal rope flux from this external flux density measurement.

Figure 3 illustrates the principles used. As in the LF method, strong permanent magnets induce a longitudinal magnetic flux in the rope. Hall generators or flux gate sensors are positioned between the permanent magnets and the rope or, alternatively, in the return flux path of the magnetic circuit to measure the magnetic flux which returns from the rope through the air gap and the permanent magnet yoke. The returning flux is a function of the metallic volume of the rope section positioned between the poles. The flux density in the air gap or in the yoke is therefore an approximate measure of the average metallic cross-sectional area of the rope section between the poles.

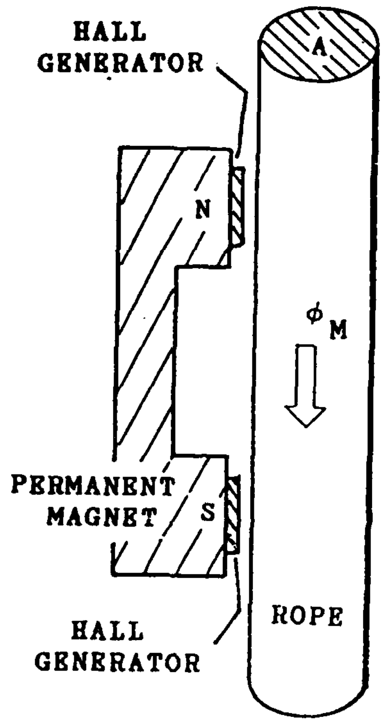


Figure 3: DC Main Flux Method with Hall Generators in Air Gap

Since these instruments measure the magnetic flux which returns from the rope through the air gap and the permanent magnet yoke, they could be called "*LMA return flux*" instruments.

In addition to the LMA sensor, an LF sensor is usually also incorporated in these instruments. Although these combined *LMA/LF return flux* instruments represent a considerable improvement over the above mentioned AC and DC test instruments, they still suffer from a rather low quantitative resolving power. Considering Figure 3, it becomes obvious that the resolving power depends on the distance of the magnetic poles. These instruments measure only an average value of a rope's metallic cross section between the poles: Any loss of cross-sectional area has to be uniform and longer than the distance between the magnetic poles to be indicated to its full magnitude.

For presently available *return flux* instruments, the pole distance is approximately 20 inches or more. Correspondingly, the loss of cross-sectional area has to be uniform and longer than approximately 20 inches to be indicated to its full extent. These instruments cannot detect and quantitatively evaluate geometrically small or even medium sized flaws such as localized corrosion, abrasion, or clusters of broken wires. Since most corrosion and abrasion occurs in localized patches, the actual estimate of remaining rope strength is still unreliable.

The resolution of the LMA sensor in *return flux* instruments is not as good as the resolution of their LF sensor. Remarkably, therefore, quantitative estimates of remaining rope strength rely to a considerable extent on the (qualitative) LF signal rather than the (supposedly quantitative) LMA signal [24]. Quantitative signal interpretation, to estimate the actual loss of rope strength, for *return flux* instruments is complicated, if not impossible. Tests are quantitatively evaluated by proprietary procedures, which are not in the public domain and cannot be critically scrutinized. Their reliability must, therefore, be questioned and considered with considerable skepticism.

2.2.2.4. LMA/LF Main Flux Instruments

To overcome these problems, NDT Technologies, Inc., under the present contract and supported by the Office of Naval Research, has developed a new class of LMA/LF instruments with improved quantitative resolution. In contradistinction to the above described *return flux* rope testers, these new instruments measure the longitudinal magnetic main flux in the rope directly. Therefore, their resolving power is better, by an order of magnitude, than that of any of the *return flux* instruments, making data interpretation easier and more reliable.

The new approach allows a direct measurement of the longitudinal magnetic main flux inside the rope, which is not possible with the *return flux* method. Therefore, in contradistinction to the above mentioned *LMA return flux* method, the present approach can be called *"LMA main flux"* method. The *LMA main flux* method offers maximum possible resolving power.

Main flux instruments use sense coils to measure the longitudinal magnetic flux inside the rope. As compared to Hall generators and flux

gate sensors, which must be physically inserted into the magnetic flux path, sense coils have an inherent advantage: They only have to encircle the magnetic flux to be measured. Therefore, coils are well suited for measuring the flux inside a rope. Hence, *main flux* instruments can measure the longitudinal magnetic flux inside the rope directly, with great accuracy and resolution.

The underlying principles of the new *main flux* instruments will be described in the next section.

Main flux Instruments have the following advantages:

- The quantitative resolution of the new instruments is better by an order of magnitude than that of any other LMA instrument.
- The reduction of metallic cross-sectional area caused by continuous defects, such as abrasion and corrosion, can be determined quantitatively with a quantitative resolution of approximately 2 inches.
- The reduction of metallic cross-sectional area caused by localized defects, such as broken wires or corrosion pitting, can be determined quantitatively with a quantitative resolution of approximately 2 inches.
- Localized defects, such as broken wires with gap lengths less than approximately 2 inches, can be qualitatively detected and evaluated.
- Using a computer assisted quantitative defect identification method, a quantitative evaluation of localized flaws with any gap length is possible.
- Because of the high penetration ratio of the sensor, the signal-to-noise ratio and penetration depth is better than that of most presently available leakage flux instruments which use differential coils.
- Signal amplitudes are independent of rope speed.

3. A NEW MAIN FLUX INSTRUMENT FOR THE QUANTITATIVE DETERMINATION OF WIRE ROPE CROSS-SECTIONAL AREA

3.1 Operating Principles

Figure 4 illustrates the underlying principles of the new LMA/LF method [1]. Similar to the previous LF instruments, permanent magnets induce a magnetic dc flux in the wire rope in the longitudinal direction, and they magnetically saturate the rope. A concentric coil surrounds the rope. The rope then moves. Any change of the metallic cross-sectional area A of the rope (caused by flaws such as corrosion, abrasion or broken wires) causes a change of the main flux Φ_M in the rope. Hence, as the rope moves, the changing main flux induces a voltage in the test coil which is proportional to the derivative of the magnetic flux Φ_M. The induced voltage is integrated by the integrator circuit. The output voltage of the integrator circuit v_I is then a voltage directly proportional to the

main flux Φ_M. Since the rope is magnetically saturated, the main flux is directly proportional to the instantaneous cross-sectional area of the rope. Hence a change of v_I is a measure of the change in metallic cross-sectional area A.

The approach shown in Figure 4 was recently also proposed, independently, in [22]. However, the arrangement of Figure 4 is hardly feasible and clearly not practical because the search coil cannot be subdivided and hinged. A subdivision of the search coil is absolutely necessary to facilitate mounting the instrument on the rope.

To solve this problem, we used a novel approach which is explained by using Figure 5. Note that the configurations shown in Figure 4 and Figure 5a are identical. The arrangement in Figure 5a is now augmented by an additional coil (i.e., Coil 2) in Figure 5b. The net flux linkages in Coil 2 are substantially zero at all times, and only negligible voltages are induced in this coil as the rope moves. Hence, adding the Coil 2 voltage (which is approximately zero) to the Coil 1 voltage obviously leaves the Coil 1 voltage substantially unchanged. Coils 1 and 2 are now rearranged as shown in Figure 5c. Following the above argumentation, it is easy to see that the combined voltages induced in the Upper and Lower Coils in Figure 5c are substantially equal to the voltage induced in Coil 1 of Figure 5a. An instrument with this new coil configuration can be hinged which makes it easy to mount it on the rope. Furthermore, we can now wind the upper and lower coils with a large number of turns (several thousand). Hence coil voltages can be in the millivolt range, which greatly facilitates the difficult problem of a long-term low-drift integration required by the implemented approach.

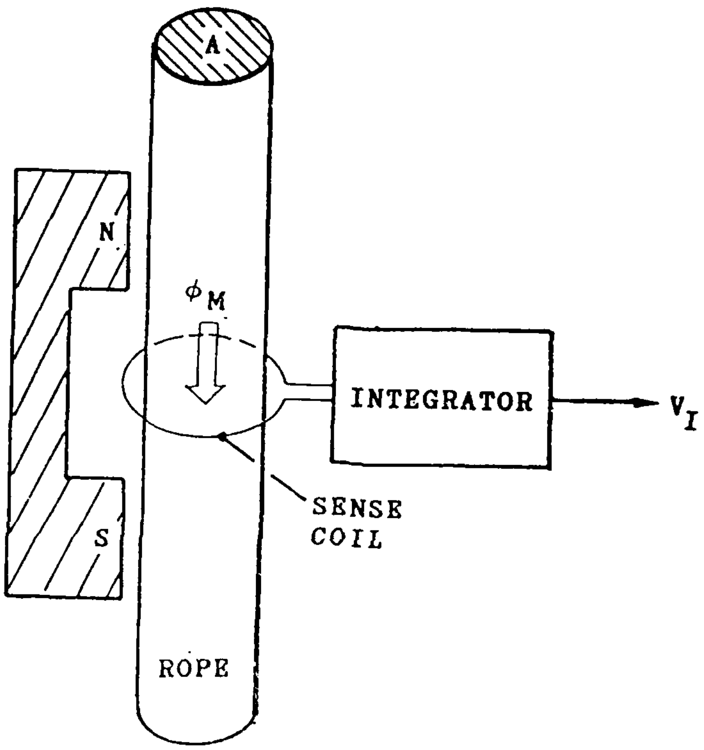


Figure 4: DC Main Flux Method with Sense Coil on Rope

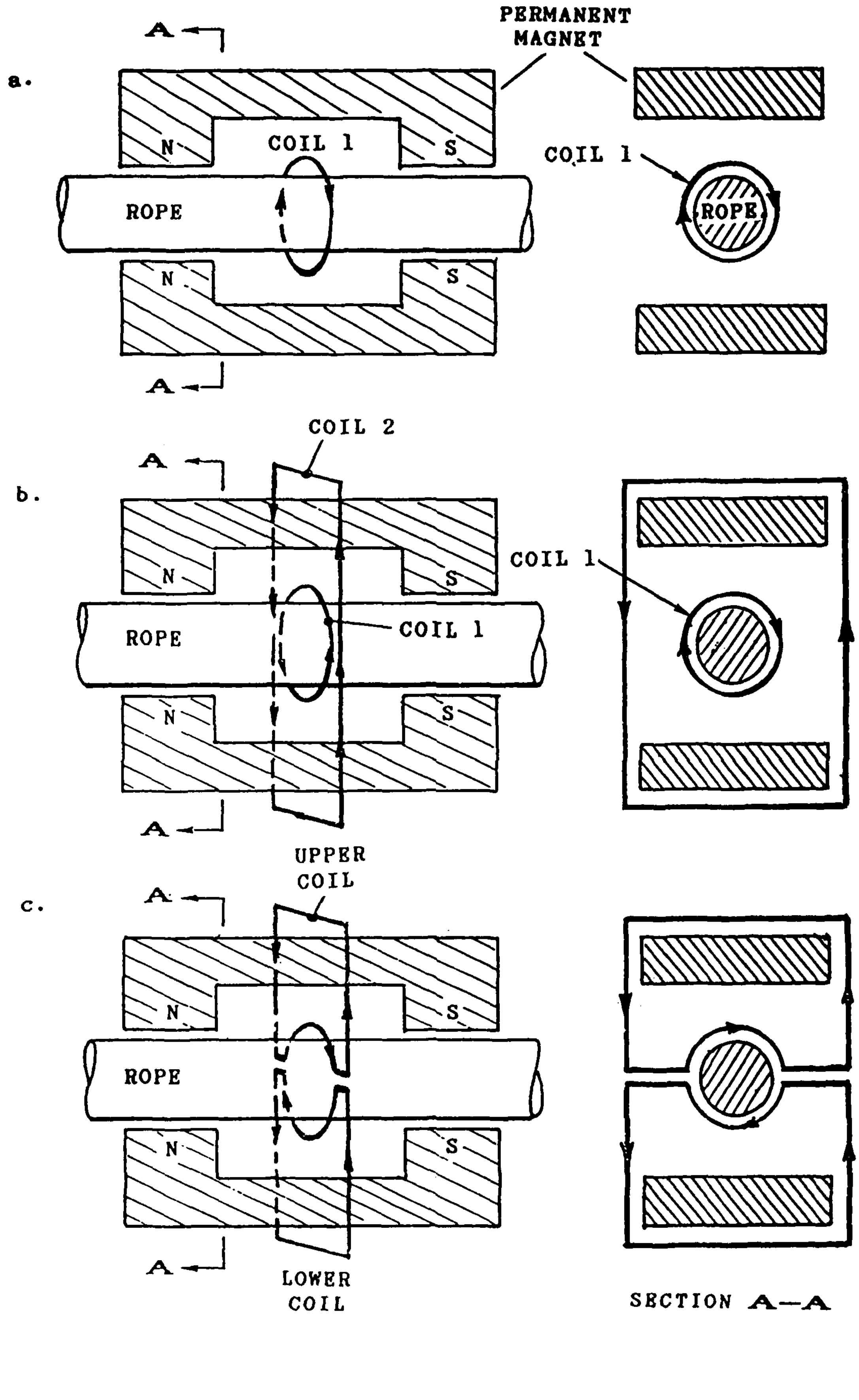


Figure 5: New DC Main Flux Instrument with Hinged Sense Coil

The problem of intrinsic noise, caused by the inhomogeneous rope structure combined with the subdivided and hinged air coil arrangement, was discussed in [1], [2]. The intrinsic noise can cause a low signal-to-noise ratio in many cases. In [1], we proposed a solution of this problem by using sense coils with ferrous cores. A ferrous core can eliminate the magnetic discontinuities caused by the subdivided and hinged air coils. Therefore, the sense coils of the implemented LMA instruments are wound on ferrous cores to eliminate the intrinsic noise caused by the inhomogeneous rope structure. Figure 6 shows this arrangement. As we have previously discussed in [1], the ferrous core guides all the magnetic leakage flux through the coils, and it eliminates the effects of discontinuities of the sense coil introduced by its subdivision.

The design and performance of the new LMA instruments is discussed in the following chapter.

3.2 Sense Coil Design

For a rational sensor design and to allow a comparison of the performance of different sensors, we have formulated the performance criteria of Section 2.2.1.

In optimizing the above design criteria, only sensitivity causes no problems. Sensitivity can easily be increased by increasing the gain of the signal amplifiers and/or the number of turns of the sense coils.

The problems associated with signal-to-noise ratio, repeatability and penetration are somewhat related. They are discussed in the following.

In previous designs [2], we identified the subdivided and hinged sense coils together with the nonhomogeneous rope structure as the primary cause of intrinsic noise. A steel wire rope is an arrangement of separate wires wound in a helical shape to form strands. The strands are then laid together in a helix to form the rope. The strands cause a leakage flux field parallel to the strands as shown in Figure 7. The flux surrounding the rope has an axial component B_z and an azimuthal component B_φ. Since previous designs used subdivided search coils as in Figure 1, the azimuthal field component induced a noise voltage in the sense coil as the rope moved. We called this noise voltage "Intrinsic Noise" [2].

The amplitude of flaw related pulses depends on the location of the flaw within the rope (its eccentricity). The closer the flaw is to the sense coil, the higher is the corresponding flaw signal amplitude. Since the inhomogeneous rope surface, which is very close to the sense coils, primarily causes the intrinsic noise signal, the signal-to-noise ratio can become quite small. The intrinsic noise is superimposed on defect signals and can significantly distort the defect signals. The defect signals are used to estimate the defect parameters, and this can introduce errors in the flaw parameter estimate.

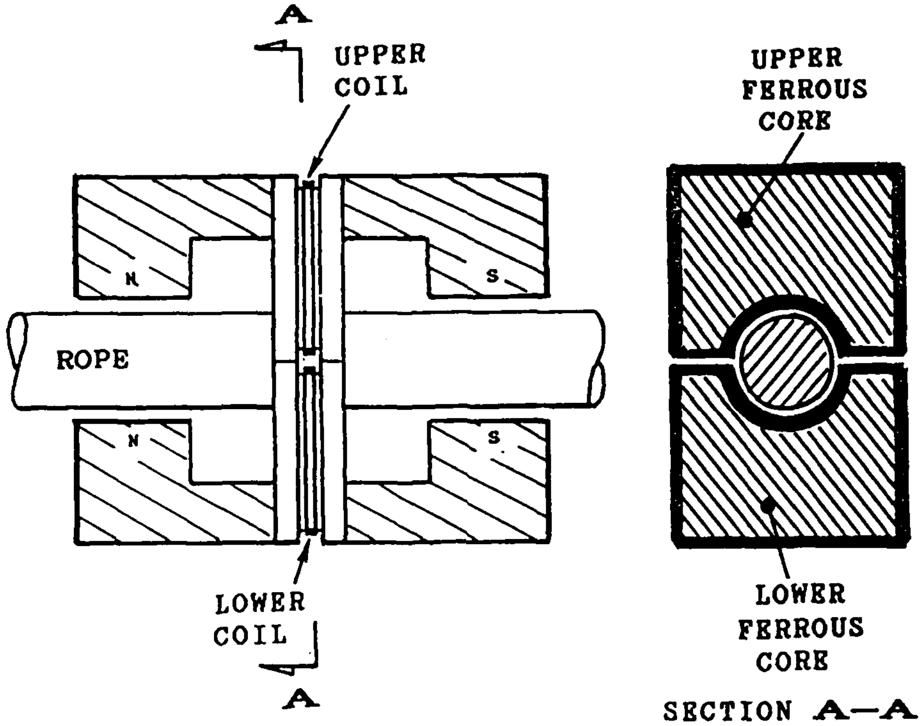


Figure 6: Coils with Ferrous Core

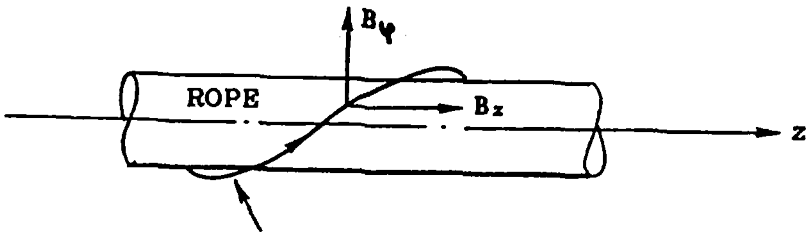


Figure 7: Azimuthal Leakage Field

Furthermore, in previous designs the subdivided coils were not rotationally symmetric [2], [3]. Therefore, noise as well as flaw signals depended on the azimuthal position of the rope with respect to the sense coils, and complete repeatability of signals could not be assured.

To remedy this situation, we used subdivided sense coils with iron cores for the new instruments. Figure 6 shows a schematic of this new coil arrangement. Note that the iron core can have complete rotational symmetry without an air gap at the subdivision. The ferrous core guides the leakage flux through the coils. Therefore the sense coils enclose the total magnetic leakage flux. Because of its rotational symmetry, the coil is now completely insensitive to the azimuthal component of the leakage field. Therefore an improved signal-to-noise ratio was achieved. Furthermore, since the coil is rotationally symmetric, we have eliminated the influence of the angular defect position on the test signal, with an improved repeatability of the test signal. The basic coil performance was not changed by the insertion of ferrous cores. Hence, most conclusions of this report hold equally well for air and ferrous cores.

The coils shown in Figures 5 and 6 have a relatively complicated shape and their manufacture requires significant craftsmanship. Therefore, for smaller instruments, we chose a simpler coil design. Figure 8 shows the simplified design. Here the sense coils are wound directly on the permanent magnet yoke. Steel pole pieces channel the magnetic leakage flux through the permanent magnet yokes. The sense coils measure the changing magnetic flux in the yokes. The simplified design is much easier to manufacture and less expensive than the coils of Figure 6. However, since the simplified design is not rotationally symmetric, it has a slightly lower signal-to-noise ratio and signal amplitudes depend slightly on the angular position of the flaw with respect to the sense coils.

The LMA trace shows continuous flaws and localized flaws, such as broken wires, with considerable accuracy. However, a differential sensor arrangement is better suited to highlight rapid flux changes caused by localized flaws such as broken wires. Therefore, a localized flaw (LF) signal of the differential type is highly desirable. In the early designs of the new LMA instruments, we used the time derivative of the LMA signal as the LF signal. This approach, however, makes the LF signal amplitudes proportional to speed. If the LF signal is to be used for a quantitative defect evaluation, obviously it must be speed independent. To make the LF signal independent of speed, we chose a differential coil arrangement as in Figures 8 and 9. In this configuration, two coils of the above design, spaced an incremental distance apart, are used. The two LMA signals from both coils are subtracted. The difference signal serves as the LF signal. It is easy to see that this difference signal is substantially the spatial derivative of the LMA signal. The spatial derivative of the LMA signal is independent of rope speed, as required.

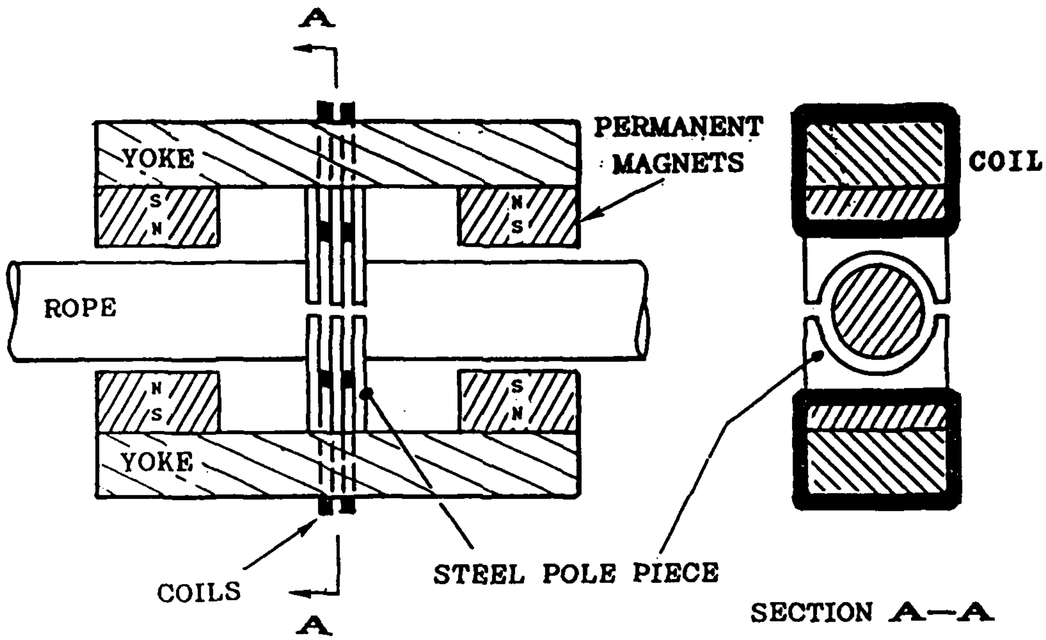


Figure 8: Simplified Sense Coil with Ferrous Core

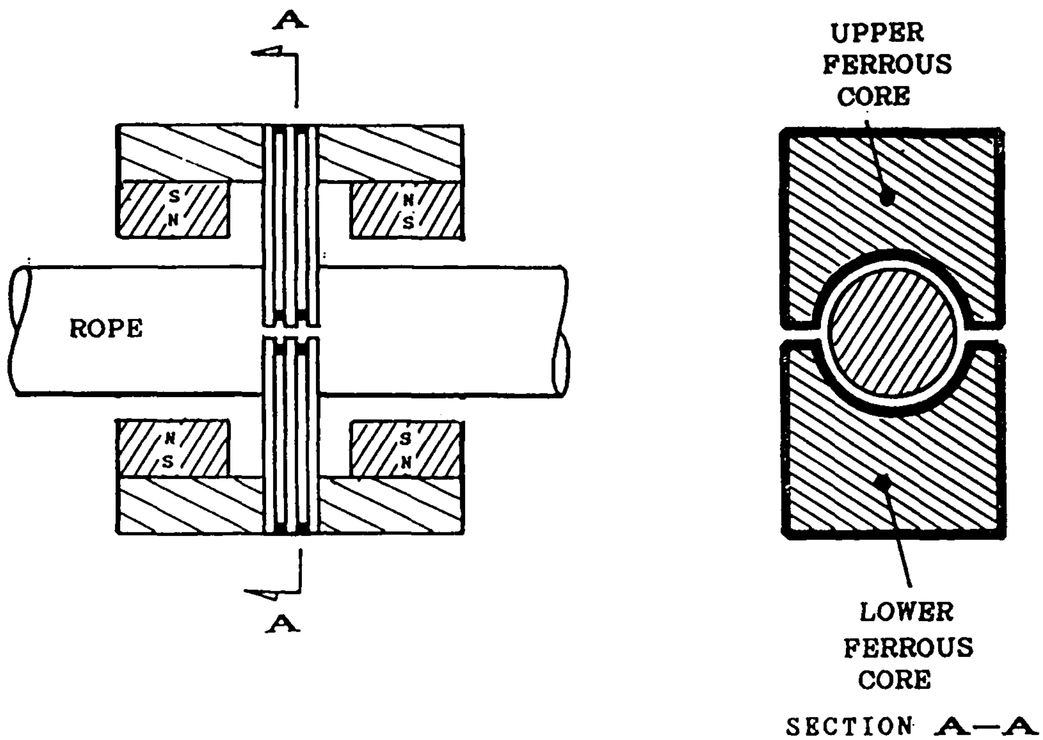
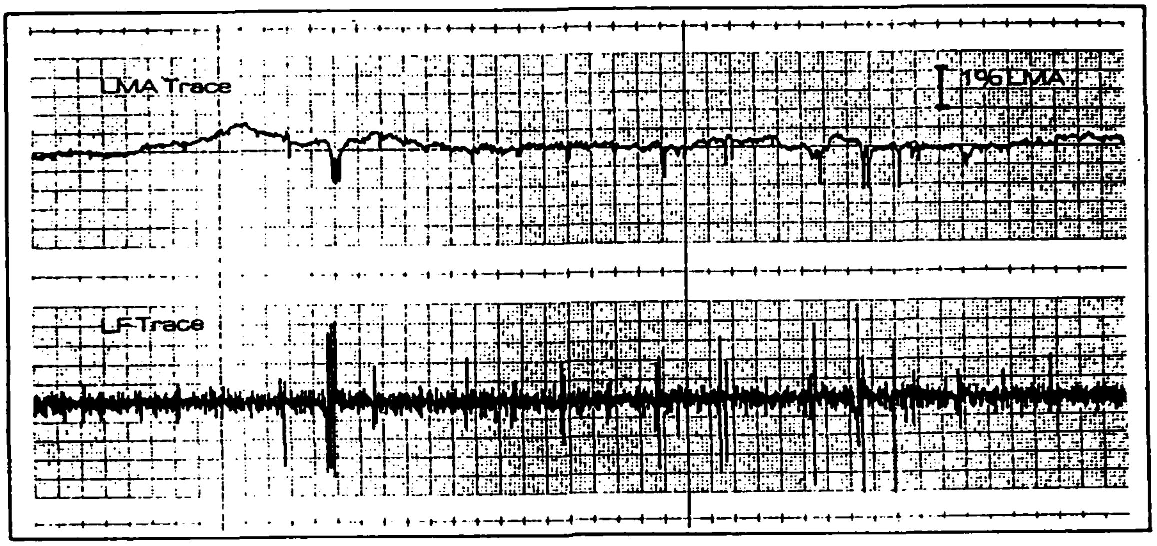


Figure 9: Double Coil Array

The coils of the new design have an excellent resolution as compared to the LMA sensors of competing instruments. Figure 10 shows a performance comparison of one of the new prototype main flux instruments with a Canadian main flux instrument. Although the scales of both strip chart recordings are different, this figure shows the drastically improved resolution and quantitative resolution of the new instruments. The new instruments have a quantitative resolution of approximately 2 to 3 inches, depending on the design. In comparison, the quantitative resolution of other instruments is approximately 20 inches [24], [25].

The importance of a high quantitative resolving power was discussed in Section 2.2.2.

NEW PROTOTYPE LMA INSTRUMENT



PREVIOUS STATE-OF-THE-ART INSTRUMENT

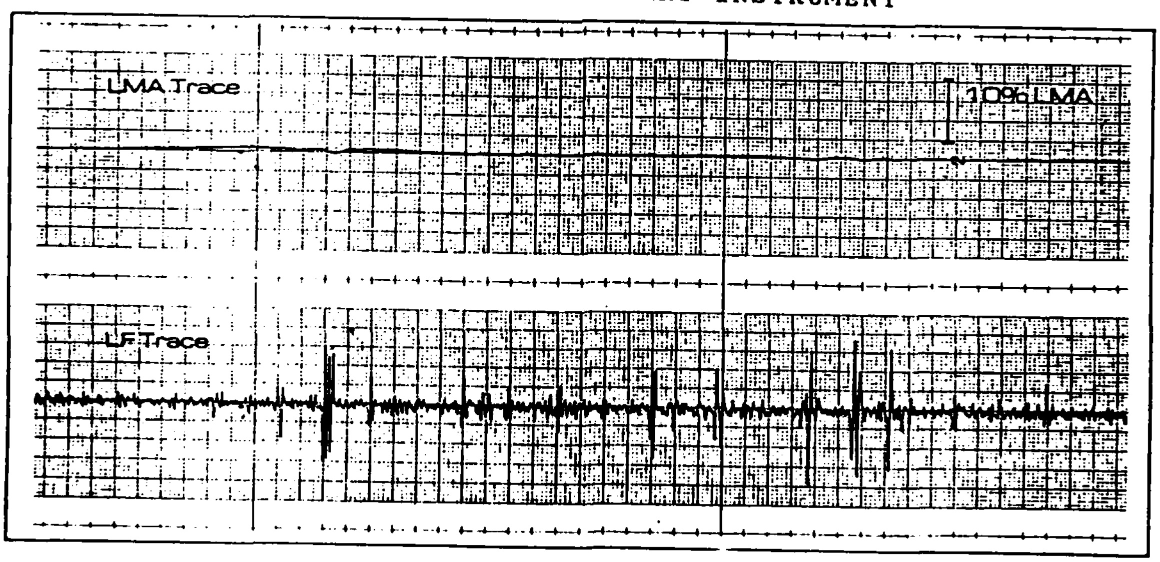


Figure 10: Performance Comparison of New LMA Main Flux Instrument with Previous State-of-the-Art Instrument

3.3 Rope Magnetization and Re-Magnetization

Magnetic flux patterns within the rope and the sense head are very complex. This, under certain conditions, causes the new instruments to behave in a fashion which is not immediately obvious. One such peculiar behavior could be called the "Remagnetization Effect". The exact mechanism of the Remagnetization Effect is still not completely understood. We conducted a substantial number of experiments to investigate this phenomenon. Unfortunately, these experiments were very expensive and time consuming.

A description and the most plausible explanation of the Remagnetization Phenomenon is presented in the following.

Consider the strip chart recording of Figure 11. To make this recording, the test rope was first completely demagnetized. The instrument was then mounted on the rope at Position 1 on the recording, and the integrator was reset. As the steel rope moves through the sense head, the strong permanent magnets in the sense head permanently magnetize the rope. The presence of remanent residual magnetic flux in the rope causes a redistribution of the flux pattern within the rope and the sense head. As the rope moves, the changing permanent residual flux causes additional increasing magnetic flux inside the instrument which, for the first two or three feet of rope movement, induces an additional voltage in the sense coils. The previously zeroed LMA signal accordingly shows an increase as in Position 1 of Figure 11. This means, the redistributed flux causes an offset of the zero setting of the LMA signal which compromises the readings of the LMA channel if not properly accounted for.

Now consider Position 2 of Figure 11. The test rope is spliced and forms a loop. (The splice is clearly visible in the chart recording). Because the rope forms a loop, Positions 1 and 2 are geometrically identical on the rope. Note that, if the instrument is located between Position 1 and Position 2 on the rope during the first circulation of the loop, that section of the rope which enters the instrument is unmagnetized, and the section of rope which leaves the instrument becomes permanently magnetized. Therefore, during the first circulation, the magnetic state of the rope changes from "unmagnetized" before Position 2 to "permanently magnetized" after Position 2. As Position 2 on the rope approaches the instrument, the changing magnetic state of the the rope again influences the magnetic flux in the instrument. This, as previously in Position 1, causes another rise of the LMA signal at Position 2 on the chart. After the first complete circulation of the loop, the rope is magnetically homogenized and no further offsets of the LMA trace occur.

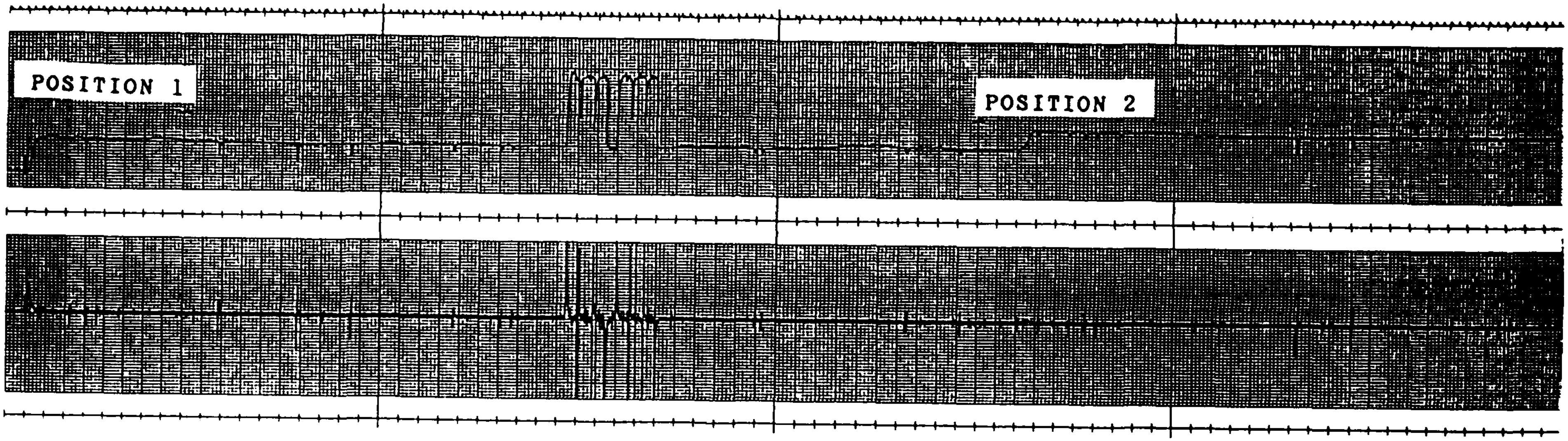


Figure 11: Remagnetization Effect

This Remagnetization Effect is explained further in the following.

Assume the sense head is mounted on a completely demagnetized rope. Now the rope moves a short distance. That part of the rope which leaves the instrument becomes permanently magnetized and retains a residual flux density in the direction of the rope axis. Consider the magnetic flux in the rope and the magnet assembly as shown in Figure 12. In the figure, we assume that the instrument has moved from position A to B. Figure 12 also shows a sketch of the axial flux density B_z. Note the magnetic reversal zone under the pole pieces where the magnetic flux changes directions. Over the distance A-B the rope is now permanently magnetized with residual flux density B_r. B_r causes an additional residual flux O_r whose path in the instrument will now be traced.

Figure 13 shows a schematic of the magnetic flux pattern in the rope and in the sense head. Note that only that part O_r of the magnetic flux is shown which is caused by the permanently magnetized rope section A-B. The rope between the magnetic poles is saturated and represents a high reluctance magnetic path for O_r. The yoke is not saturated and represents a low reluctance magnetic path. Therefore, a major portion of O_r returns through the yoke, as indicated. The increasing residual flux O_r causes a rise of the LMA signal, simulating an increase in metallic cross-sectional area. This becomes obvious by considering the leakage flux O_l which would be caused by a decrease of metallic cross-sectional area. O_l and O_r have opposite directions. Therefore, O_r is recorded as, and simulates, an increase of metallic area.

This explanation of the remagnetization effect suggests a solution of the problem. The effects of remagnetization can be reduced by increasing the incremental reluctance of the yoke. We conducted several, fairly involved experiments to verify this hypothesis.

The experiments showed that a simple reduction of the yoke's cross-sectional area is not feasible. This approach drives the magnet assembly into saturation and increases the incremental reluctance of the yoke, as postulated. However, by the same token, it increases the reluctance of the magnetic circuit and keeps the rope out of saturation. This, in turn, reduces the LMA signal amplitudes and decreases the measurement accuracy.

An increase of the magnetic field, by adding permanent magnets, drives both, the yoke and rope, into saturation and increases the incremental reluctance of the yoke. Experiments show that this method is indeed feasible. It is presently being used for the design of additional prototype instruments. An increase of the number of permanent magnets can significantly reduce the effects of remagnetization.

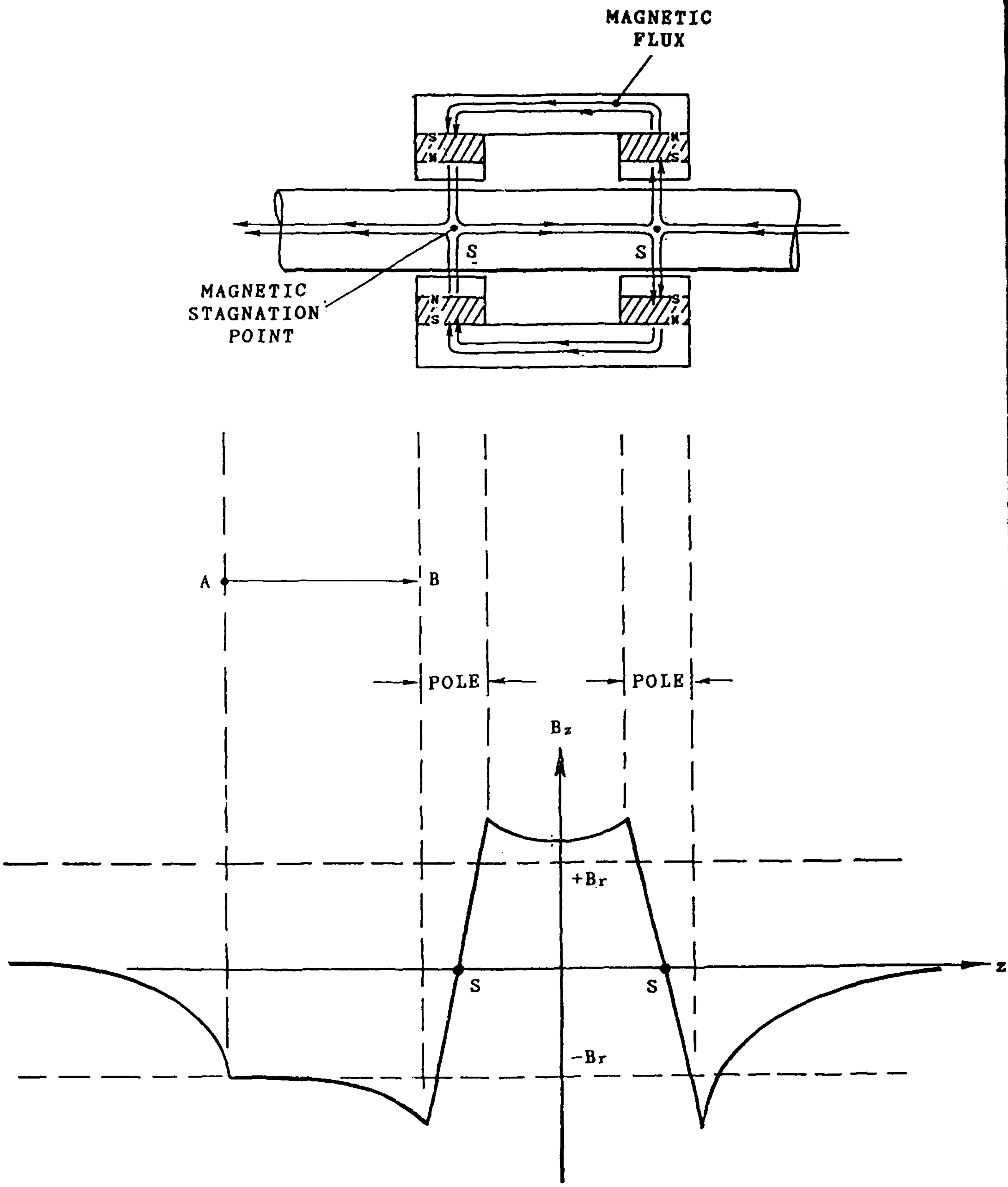


Figure 12: Magnetic Flux in Magnetizer and Rope

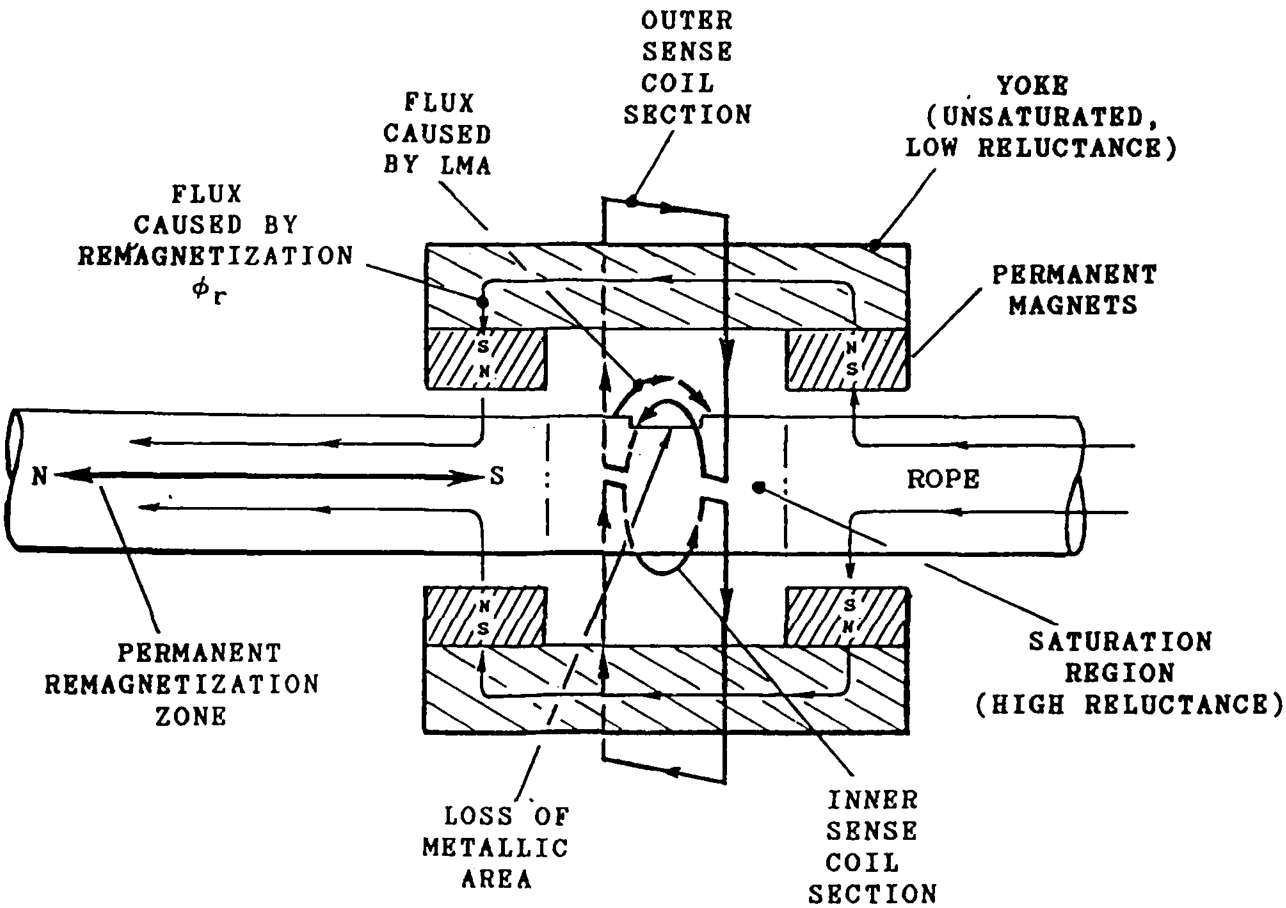


Figure 13: Magnetic Flux Caused by Remagnetization

Note that the problems caused by the remagnetization effect can be bypassed by magnetically homogenizing the rope before the inspection. The rope is homogenized by simply moving it through the instrument over its entire length. After the homogenization, the integrator voltage is reset to zero and the rope is inspected in the usual fashion. This procedure completely eliminates the effects of remagnetization. Magnetic homogenization of the rope, before the inspection, is a good practice. If feasible, the rope under test should be homogenized before the inspection.

Note that the LF signal is not affected by remagnetization. This signal is derived by subtracting the two signals from the differential coil arrangement shown in Figure 8. Therefore, the effects caused by rope remagnetization are subtracted and cancel.

3.4 Echo Effect

Another peculiar behavior of the new instruments is the so-called "echo effect". This phenomenon is illustrated by the strip chart recording of Figure 14. A small replica (an "echo") of the flaw signal appears immediately before and after the actual flaw signal. The amplitude of the echo signal is less than 20% of the flaw signal and contributes to the intrinsic noise. While the signal-to-noise ratio of the new instrument compares very favorably with the signal-to-noise ratio of other instruments, elimination of the echo effect would undoubtedly improve the performance.

For an explanation of the phenomenon we first consider the magnetic field within the rope and the magnet assembly. Figure 15 shows the magnetic flux in the instrument. In particular, note the magnetic reversal zone under the pole pieces where the magnetic flux changes directions. Figure 15 also shows a sketch of the axial flux density B_z for a completely homogenized rope. The axial flux density within the rope changes its direction twice as the rope moves through the magnet. Outside the magnet, the direction of the axial flux density is opposite to the direction of the flux density inside the magnet. A permanently magnetized and homogenized rope regains its residual flux density after moving through the magnet.

Without changing any signals, the outer part of the sense coils could now be replaced by the (hypothetical) equivalent coils indicated by dotted lines in the figure. This is plausible because the outer coils can be moved to the position of the equivalent coils substantially without cutting any flux lines, i.e., without inducing any additional voltages in these coils.

The rope is magnetized inside and outside the magnetizer assembly, as in Figure 15, and any rope flaw causes a distortion of the magnetic flux. Therefore, upon approaching the instrument, any irregularity in the rope is first sensed by the outer part of the sense coils (or, according to the above discussion, by the equivalent coils). This causes the first "echo". The discontinuity is then sensed by the inner part of the sense coil which gives the actual flaw signal. The outer part of the sense coil senses the discontinuity again while it moves away from the instrument. This causes the second "echo". Note that the magnetic flux density inside and outside the magnet and the coil orientations are such that the LMA signal and its two echoes have the same polarity.

Based on these findings, we modified the coil simulation program, considering the above described axial flux density in the rope together with the voltages induced in the outer sense coil. The simulated LMA signal of a step change of metallic area and the corresponding experimental signal are shown in Figure 16. Note the agreement between simulation and the experimental results.

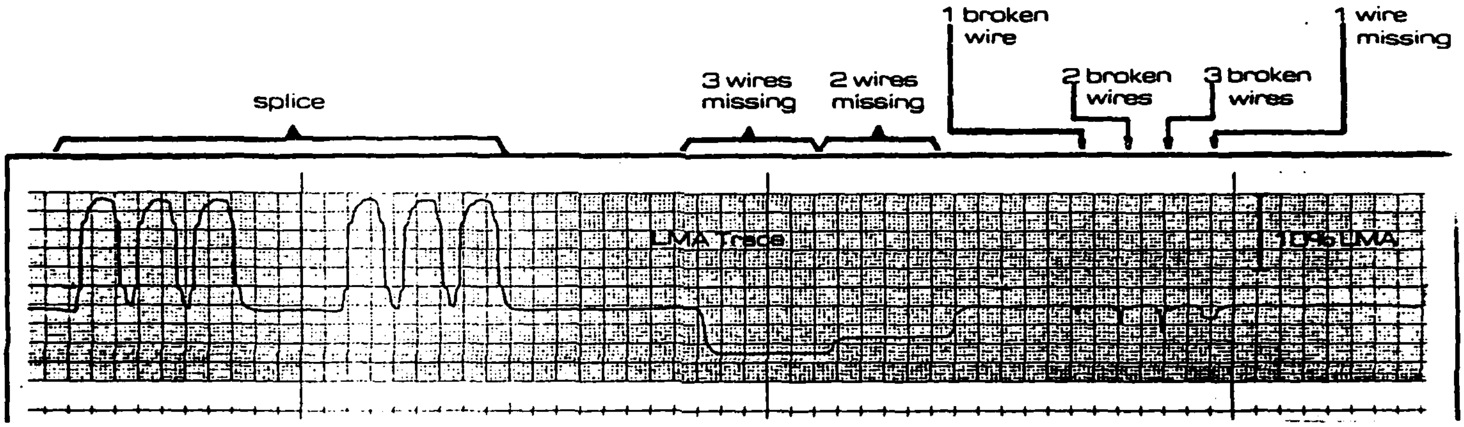


Figure 14: Echo Effect

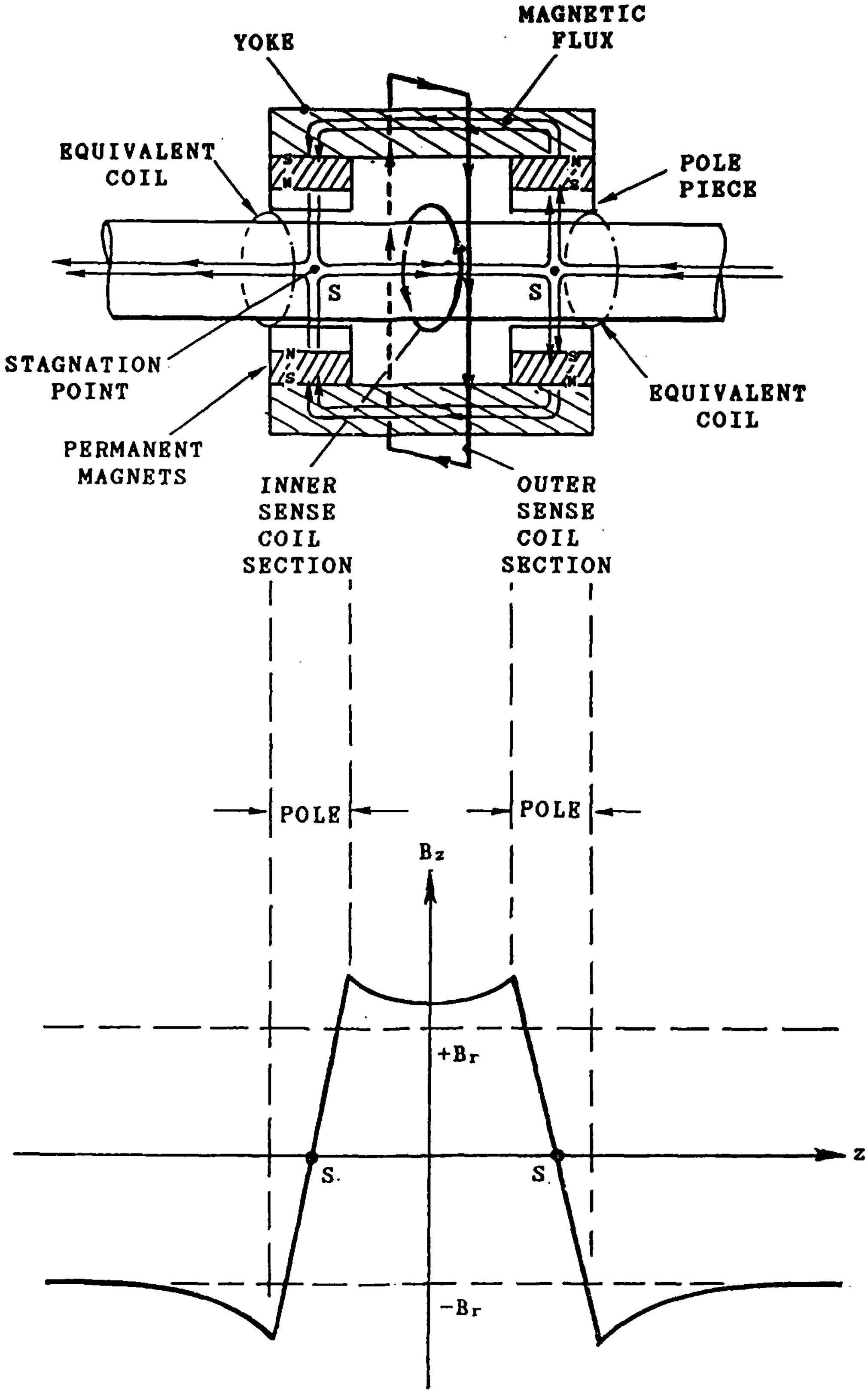


Figure 15: Echo Effect: Magnetic Flux Patterns

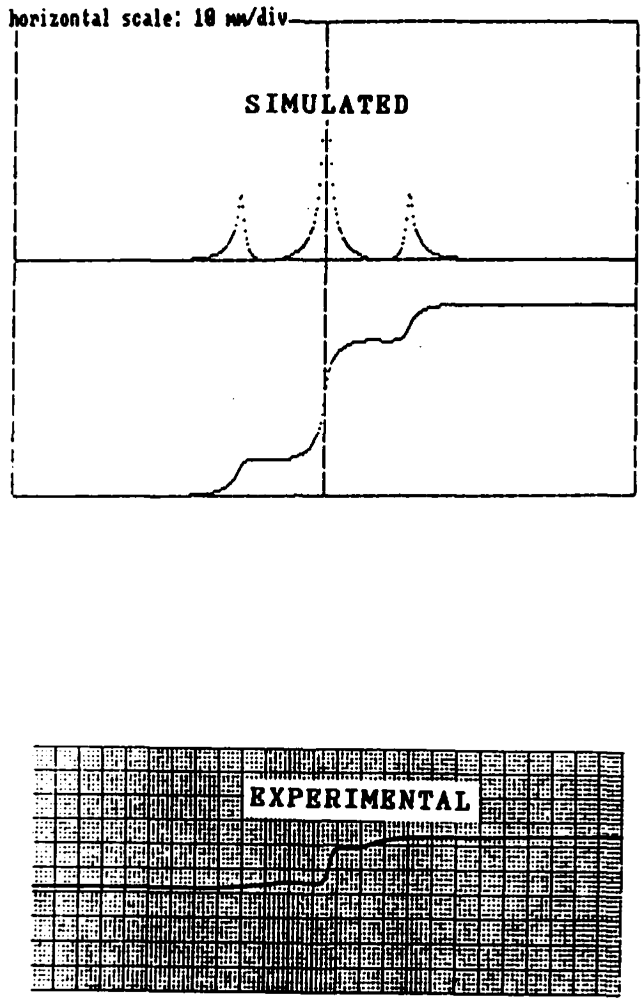


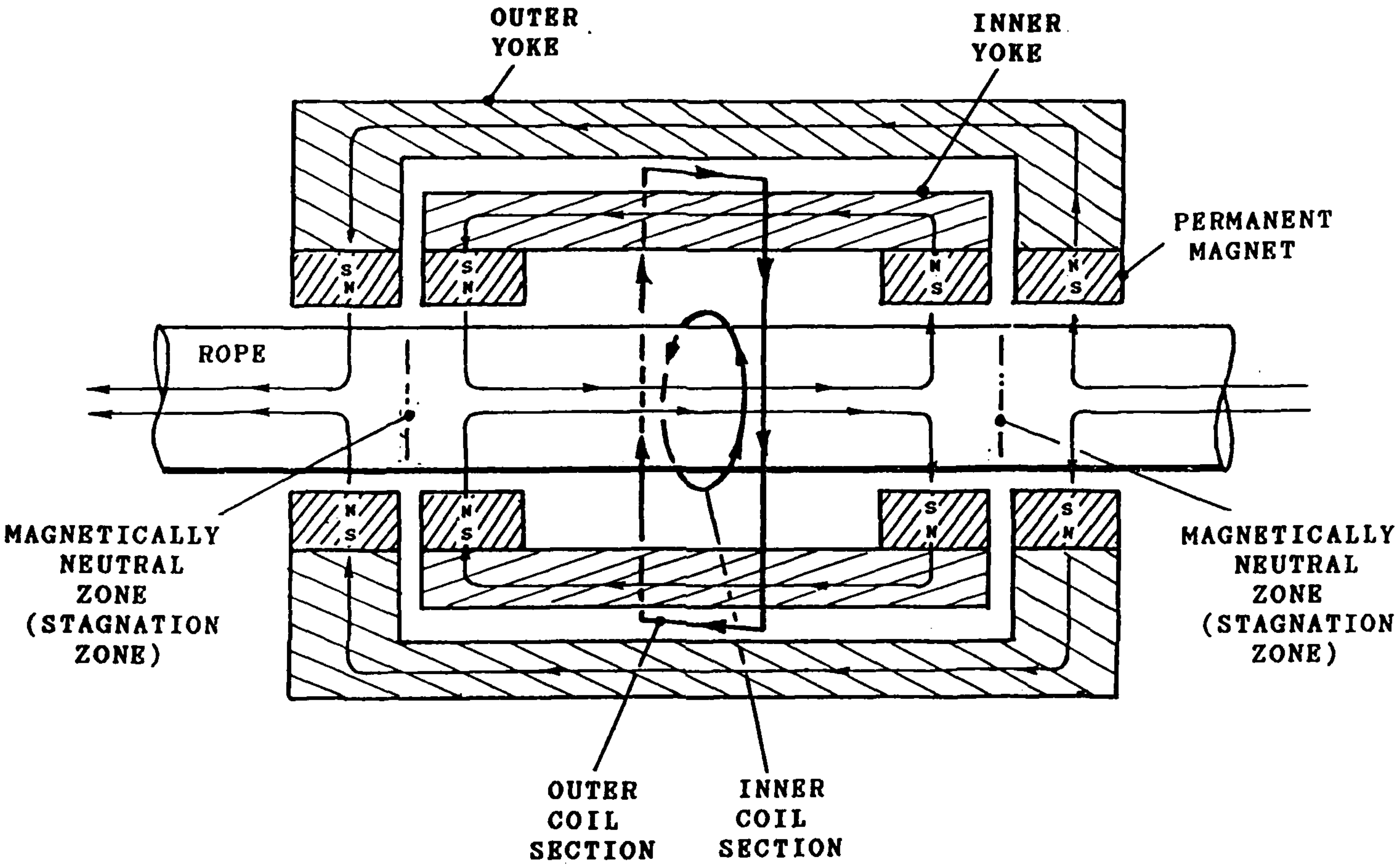
Figure 16: Echo Effect:
LMA Step Response:
Simulated and Experimental Results

Encouraged by computer simulation results, we made several attempts at eliminating the echo effect by placing the outer return coils into a magnetically neutral zone (the magnetic reversal zone in Figure 15). Figure 17 shows this arrangement. In this case, the magnet assembly was split into two pieces and the outer return coil was placed into the magnetically neutral zone between the two magnetizer pieces as shown in the figure. While the experimental results were consistent with the simulated results, the signals became very noisy. This noise is probably caused by the rapid reversal of the magnetic flux in the magnetically neutral reversal zone. Because of the inhomogeneous rope structure, the flux reversal area moves slightly back and forth in a random fashion. This movement induces additional noise voltages in the outer part of the sense coils. Therefore, we did not pursue this approach any further.

As stated above, the new instruments have a significantly better LMA signal-to-noise ratio and resolution than other instruments. Therefore, we decided to postpone any further attempts to reduce the echo effect.

Note that the LF signal does not show an echo effect. This signal is derived from the differential coil arrangement of Figure 9. Therefore, the echoes in the LF signal cancel.

Figure 17: Split Pole Arrangement



4. COMPUTER-AIDED QUANTITATIVE DEFECT IDENTIFICATION

The quantitative resolution of the LMA sense coils is approximately 50mm which is a considerable improvement as compared to the previous state of the art. The quantitative resolving power can be improved further by using a computer-aided quantitative defect identification method. One approach is discussed in the following.

The geometry of a defect in combination with the sensor geometry influences the shape of the defect signal in a very complicated fashion. The sense coils and rope flaws are characterized by the following geometrical parameters (see Figure 18):

Coil Radius: R

Coil Distance: d

Flaw Eccentricity: x

Flaw Length: l

Flaw Cross-Sectional Area: q

The following parameters characterize the defect signals (see Figure 18):

Peak LMA Signal Amplitude: LMA_P

Peak LF Signal Amplitude: LF_P

LF Signal Peak Distance: s

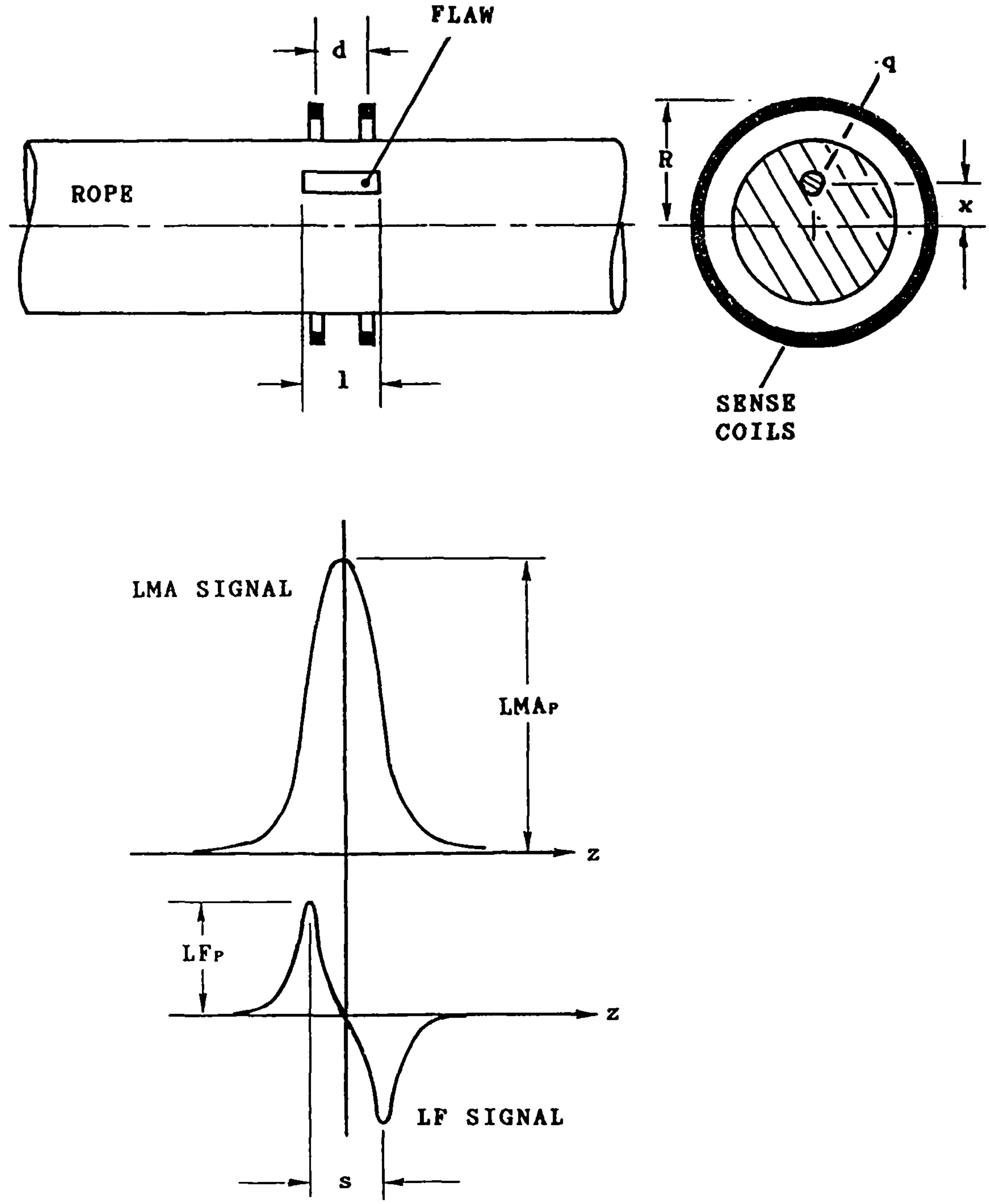


Figure 18: Defect, Coil and Rope Geometry, and Test Signal Parameters

From these signal parameters, we derive the following supplementary signal parameters:

Normal Flaw Cross-Sectional Area: q_N (Cross-Sectional Area of a Standard Calibration Wire)

Normal LMA Signal Amplitude: $LMA_{PN} = LMA_P$ for a well defined standard surface flaw with infinite flaw length and cross-sectional area q_N (e.g. missing or added wire with known dimensions)

Normal LF Signal Amplitude: $LF_{PN} = LF_P$ for a well defined standard surface flaw with infinite flaw length and cross-sectional area q_N (e.g. missing or added wire with known dimensions)

Signal Amplitude Ratio: $SAR = LF_P/LMA_P$

Normal Signal Amplitude Ratio: $SAR_N = LF_{PN}/LMA_{PN}$ (SAR of a surface flaw with infinite flaw length)

Relative Signal Amplitude Ratio: $SAR_R = SAR/SAR_N$

Relative LMA Signal Amplitude Ratio: $LMA_R = LMA_P/LMA_{PN}$

Relative LF Signal Amplitude Ratio: $LF_R = LF_P/LF_{PN}$

The above defined Normal (LF and LMA) Signal Amplitudes are easily determined by attaching a standard calibration wire with known dimensions (a "standard flaw") to the rope surface and by measuring and evaluating the corresponding flaw signal amplitudes. All other rope flaws are then evaluated relative to this standard flaw.

Any implementation of automatic defect characterization schemes using magnetic flux methods requires substantially four distinct signal processing steps [2]:

1. Test Signal Generation. Material nonhomogeneities in the test specimen cause disturbances of the magnetic field. The changing magnetic field induces the test signals in the sensors.

2. Test Signal Conditioning. To make the test signals useful for the subsequent processing, they usually have to be modified. Pre-amplification is required. Filtering and/or non-linear signal modification are often necessary.

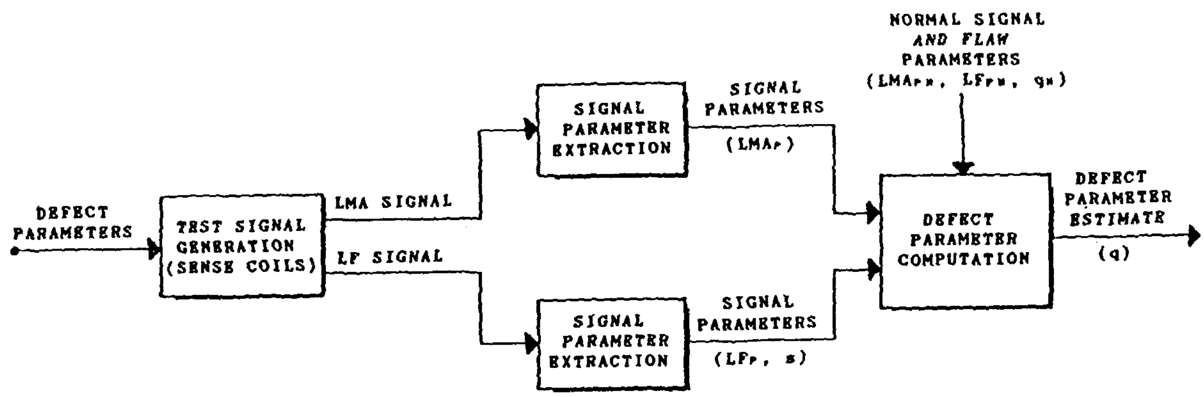
3. Signal Parameter Determination. From a practical viewpoint very few parameters are available to characterize flaw signals, either in the time domain or in the frequency domain. Characteristic parameters are flaw pulse-amplitude and pulsewidth or pulse distances (in the time domain) or signal amplitude and signal frequency (in the frequency domain). Because of the inevitable inaccuracies, caused by noise, a more detailed characterization of the test signals by more than the above parameters does not appear practical at the present time. The signal parameters are extracted from the test signals during this step.

4. Flaw Parameter Computation. The flaw geometry is computed from the signal parameters during this step.

The correspondence between signal parameters and flaw geometry is not unique, i.e. flaws of different shape and location can produce identical signals. To improve the estimate of the flaw geometry, the number of available independent signal parameters could be increased by utilizing an array of sensors. This approach was used in the Phase I study [2] where two concentric coils were used to produce two independent test signals.

The present approach uses a greatly improved sense coil arrangement which allows a direct and simple quantitative determination of a rope's metal loss for faults which are longer than approximately 2 inches. To evaluate shorter flaws, a slightly more involved quantitative defect identification approach is necessary. The use of concentric coils, as in [2], is not practical for the new sensor configuration. Therefore, the fault signal (the LMA signal) and its spatial derivative (the LF signal) are used to derive a sufficient number of independent defect parameters. The above approach can then be used to implement a quantitative defect identification scheme. Figure 19 shows a functional block diagram of the implemented automatic defect characterization method.

Figure 19: Functional Block Diagram of Defect Identification Scheme.



The qualitative defect identification approach will now be explained in an exemplary fashion by using actual examples. The coil and flaw parameters for these examples are:

Coil Radius: $R = 12.5$ mm

Coil Distance: $d = 5$ mm

Flaw Eccentricity: $x = 0 - 9.5$ mm

Flaw Length: $l = 5 - 80$ mm

To obtain the experimental test results, pieces of test wires were attached to the rope, simulating an increase of metallic cross-sectional area.

Figure 20 shows representative simulated waveshapes for a 3/4 inch (19 mm) diameter rope. Figure 21 shows corresponding actual flaw signals measured with one of the new main flux prototype instruments. Note the agreement between simulated and experimental results.

Figure 22 shows the flaw signal caused by a step change of metallic cross-sectional area which were obtained from a computer simulation [2]. Figure 23 shows the corresponding measured actual flaw signal. The area change in this case is caused by attaching an 18 inch long piece of wire to the rope. Step changes of metallic cross-sectional area will be called fundamental flaws in the following.

It is easy to see, that faults with any gap lengths l can be represented by linear superposition of the fundamental flaws and their corresponding flaw signals. Figure 20 shows simulated signals for flaws with different gap widths l and eccentricities x which were obtained from the elementary flaw signals by linear superposition. The results shown in Figure 20 illustrate how the amplitudes of the LMA signals decrease as the gap width of flaws decreases. For flaw lengths shorter than the quantitative resolution, the LMA signal does not indicate the complete metallic area loss.

Figure 24 shows the measured metallic area loss q_M as a percentage of actual metallic area loss q as a function of gap length l. This functional relationship can be approximated by

$$q_M/q = 1-\exp(-l/L) \qquad \{1\}$$

where L is a flaw distance constant. This approximate relationship {1} with L = 18mm is also indicated in Figure 24.

The actual area loss q as a function of measured area loss and flaw length can then be approximated by the following expression

$$q/q_N = (LMA_P/LMA_{PN})/(1-\exp(-l/L)) \qquad \{2\}$$

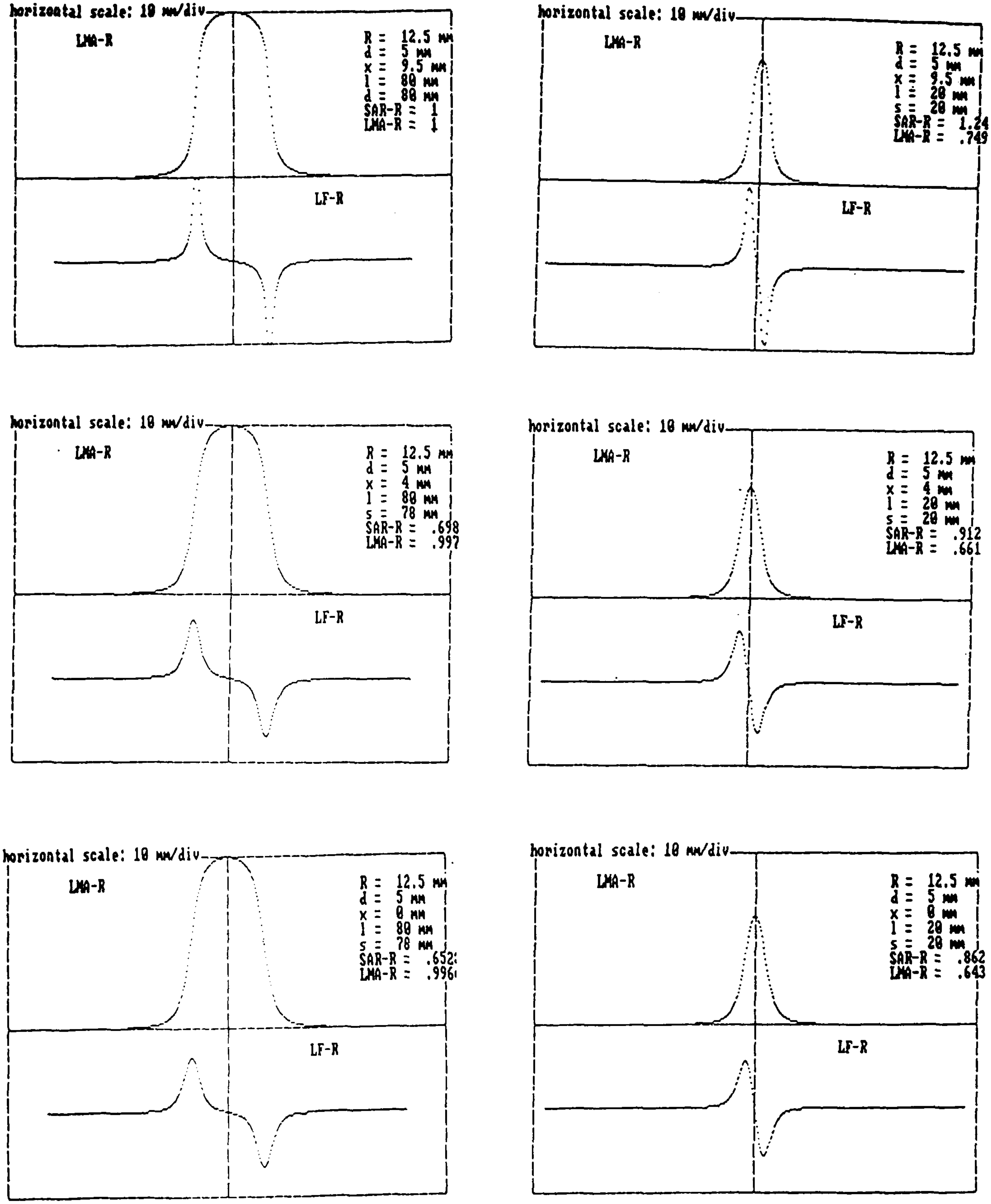


Figure 20: Defect Catalog of LMA and LF Defect Signals

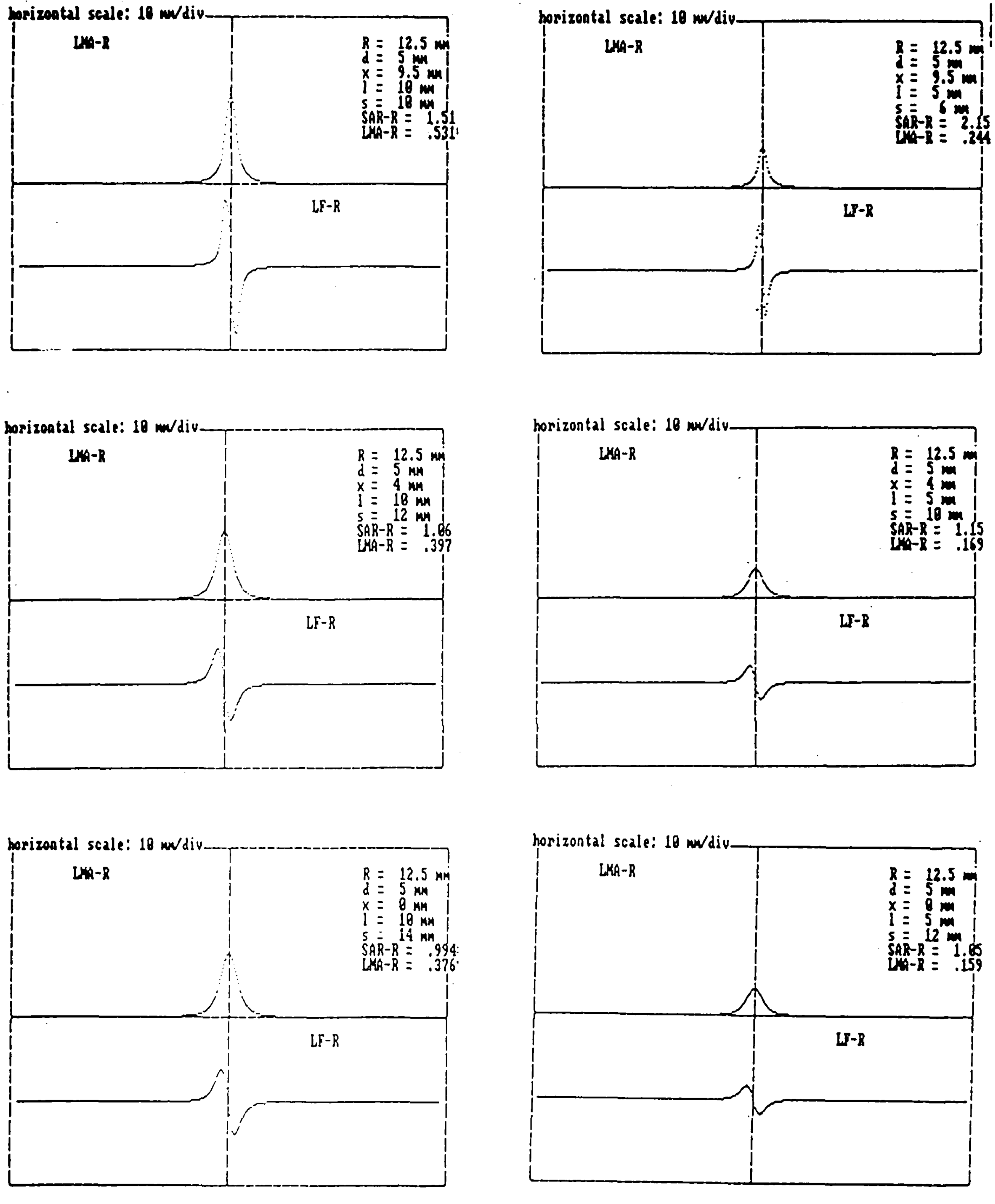


Figure 20: continued

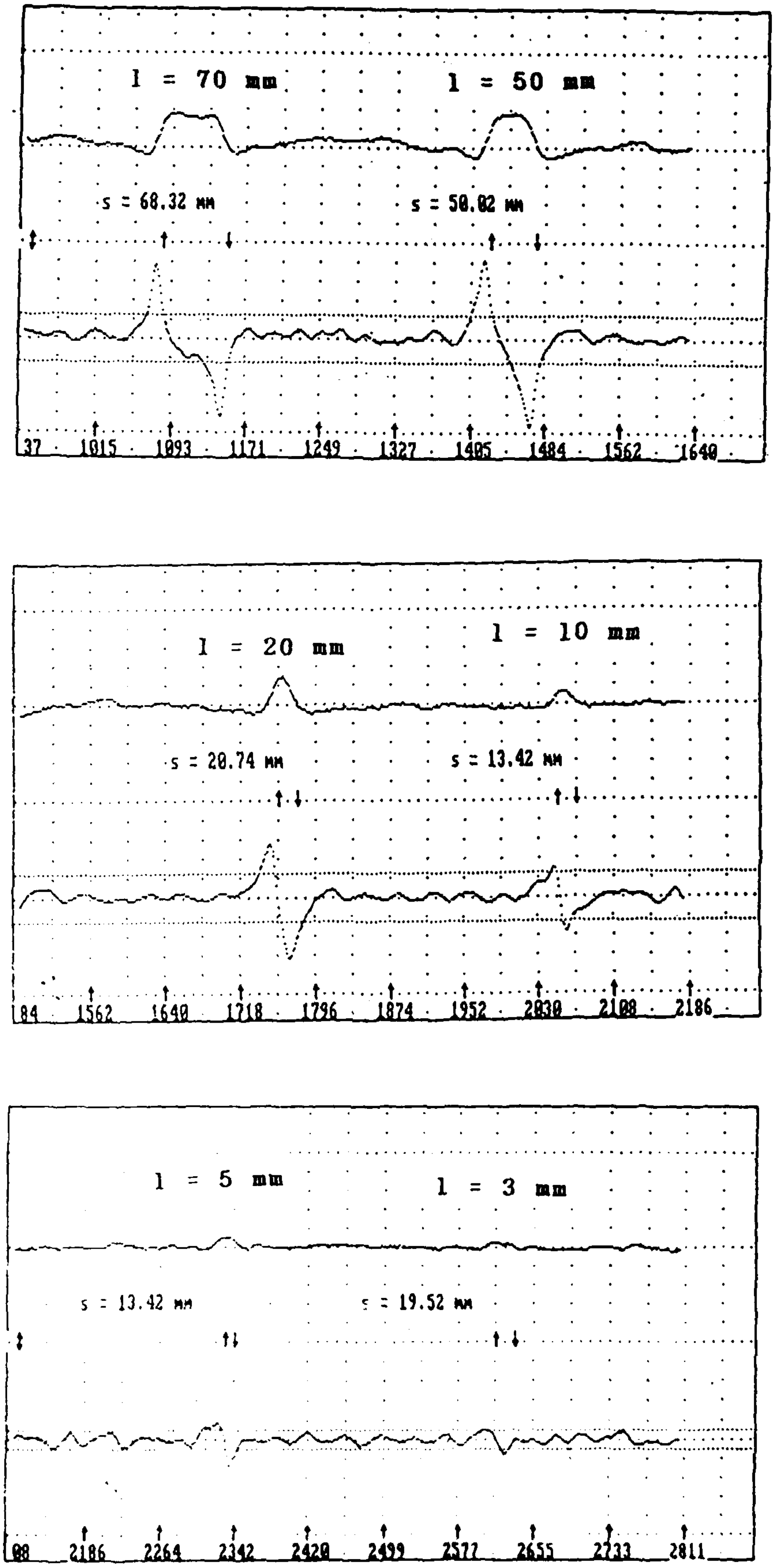


Figure 21: Measured Defect Signals

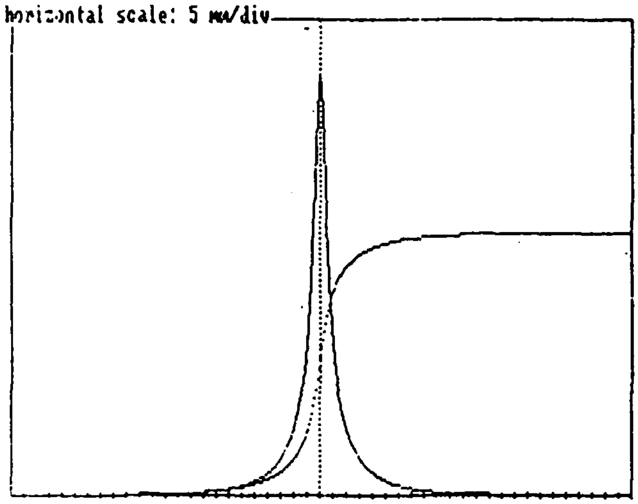


Figure 22: Simulated LMA and LF Signals
(Step Change of Metallic Cross-Sectional Area)

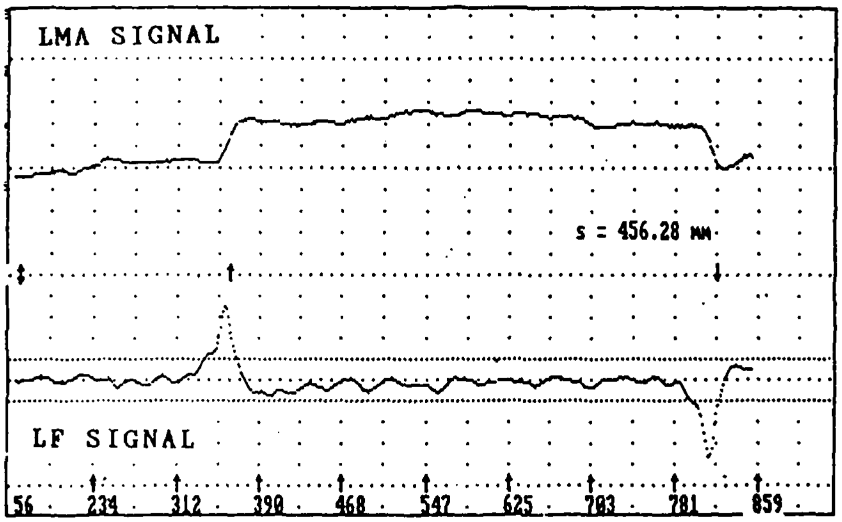


Figure 23: LMA and LF Signals for a Step Change of Metallic Cross-Sectional Area (Experimental Results)

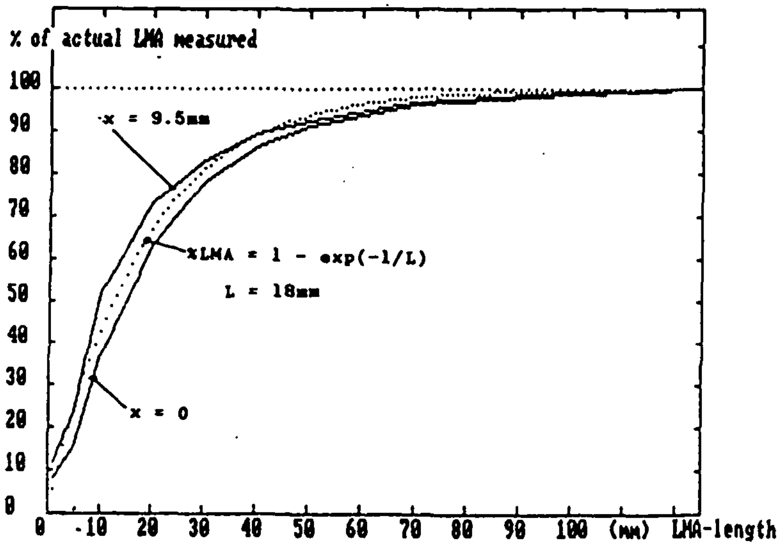


Figure 24: Measured Metallic Cross-Sectional Area Loss as a Percentage of Actual Metallic Area Loss

To calibrate the instrument for each rope, the normalized values LMA_{PN} and LF_{PN} are determined by attaching a wire of known cross sectional area q_N to the rope and by recording the corresponding LMA and LF signals. All flaws can then be quantitatively evaluated with respect to this reference wire.

To implement a quantitative defect identification scheme, we consider Figures 20 thru 24. We observe that, for flaws longer than approximately 15mm, the flaw length l is approximately equal to the peak-to-peak distance s of the LF signal. Using Figure 25, it is then simple to determine the actual flaw length l from the peak-to-peak distance s.

As illustrated by Figures 25, 20 and 21, the determination of flaw length becomes more complicated for shorter flaws. In this case, the peak-to-peak distance s is no longer a good indication of flaw length l. However, using Figure 26, the Relative Signal Amplitude Ratio SAR_R can be used to derive at least an estimate of l. Note that, for short flaws, the accuracy of the flaw length estimate is reduced further because of the inherent difficulty in establishing the flaw length for short flaws combined with the usually low signal-to-noise ratio caused by the inevitable intrinsic noise.

After we have determined the flaw length l, we use Figure 24 or Equation (2) to determine the actual loss-of-metallic-area. The quantitative defect identification is now complete.

A closer examination of Figures 20 thru 27 reveals a few features of the new sense coils which we will discuss in the following.

Since the intrinsic noise signal is primarily caused by the inhomogeneous rope surface, it can cover up signals caused by interior flaws to such an extent that they can no longer be detected. As discussed in [2], because of this, the penetration ratio has to be maximized for an optimum signal-to-noise ratio. The penetration ratio was defined above.

For short flaws, with gap widths less than 5 mm and a 3/4 inch rope, the present sensor has a penetration ratio of .72 for the LMA signal and a penetration ratio of .49 for the LF signal. This compares with penetration ratios of .22 and .40 for the comparable double-differential coils which were previously used for the Phase I research. Note that for gap widths longer than approximately 2 inches the penetration ratio for the LMA signal for the new coils is close to 1.

This implies that, because of the higher penetration ratios, the new coils offer a significantly improved signal-to-noise ratio as compared to the previous double-differential coils [2]. Furthermore, the new coils have a considerably improved capability of detecting internal flaws. These observations are borne out by the experimental results.

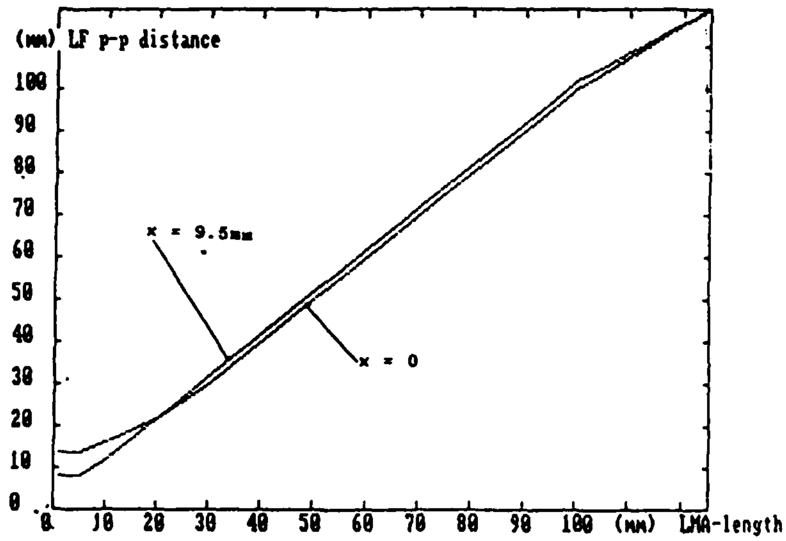


Figure 25: LMA Gap Length as a Function of LF Signal Peak-to-Peak Distance

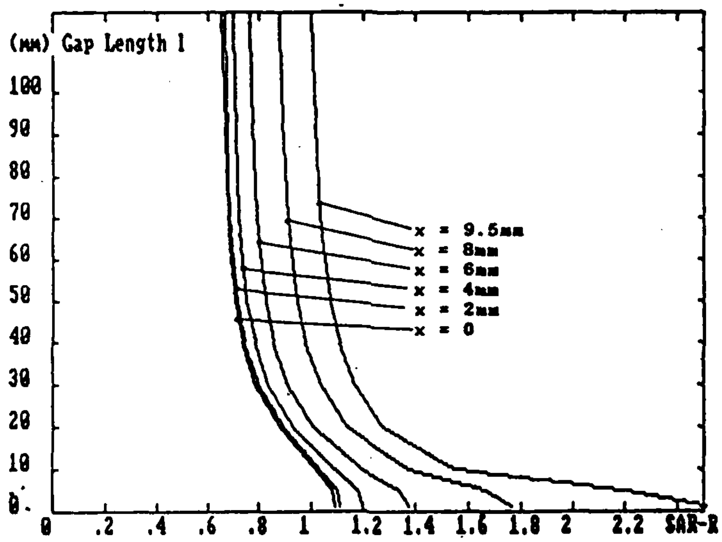


Figure 26: LMA Gap Length as a Function of Relative Signal Amplitude Ratio and Eccentricity

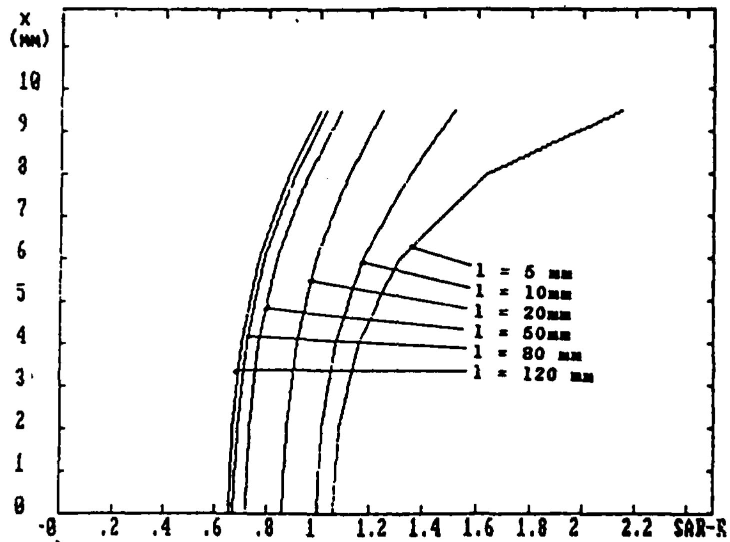


Figure 27: Eccentricity as a Function of Relative Signal Amplitude Ratio

On the other hand, these high penetration ratios indicate that, for the new sense coils, the flaw signal amplitudes are not very dependent on the flaw eccentricity x. This insensitivity, combined with inaccuracies caused by the intrinsic noise, makes a quantitative determination of the location of the flaw within the rope cross section impossible from a practical point of view. Figure 27, which shows the flaw eccentricity x as a function of the Normalized Signal Amplitude Ratio SAR_N and Flaw Length l illustrates this observation.

The quantitative determination of flaw eccentricity would undoubtedly be a desirable feature. Therefore, alternative methods for a determination of the flaw location should be investigated. Any new approach should,

however, retain the excellent performance characteristics of the present sensors.

5. INSTRUMENT FOR THE INSPECTION OF WIRE ROPE END SECTIONS.

5.1. Identification and Significance of the Problem

During operation, moving and standing wire ropes are subjected to, sometimes severe, vibrations which excite longitudinal, lateral and torsional rope oscillations. For all types of rope oscillations, longitudinal, lateral or torsional, rope terminations constitute oscillation nodes, causing a major part of the oscillatory energy in the rope to be absorbed by the end attachment.

Rope oscillations induce considerable tension, bending and torsional stresses at the rope terminations which cause the wires to fatigue and, eventually, to break. Wires can break internally and externally. Furthermore, wire breaks can occur inside the socket entrance where detection is difficult if not impossible. Wire fatigue, particularly at the nose of the socket, frequently causes early failure and maintenance problems. Rope breakage at the end attachments is a common failure mode, which makes rope terminations a critical area in assessing a rope's condition.

A typical form of vibrational fatigue occurs in installations which are subject to cyclic loading, for instance boom suspension systems of draglines. Here, the vibrational energy, induced by cyclical loading of the rope, is absorbed at the end fittings of the pendants causing eventual fatigue breakage at this point.

Another example: Normal operation of a machine or hoist induces oscillations. For instance, in shaft hoists, start up of the cage at the bottom excites low frequency oscillations in the rope. As the cage reaches the top of the shaft, the free length of rope becomes shorter and the initial slow oscillation turns into a high-frequency vibration. A major part of the vibrational energy is dissipated in the cage attachment, resulting in eventual fatigue breakage of the wires at the attachment of the cage.

Corrosion can also cause rope deterioration inside the socket. For instance, acid is often used to etch the wires before zinc socketing. If the wires are not carefully cleaned after the etching, the left-over acid can cause corrosion inside the socket. Another example: For some marine applications, end attachments are frequently submerged in sea water which causes corrosion inside the socket where detection is difficult.

5.2. Technical Approach

In the past, none of the available NDI instruments was, even remotely, useful for the inspection of wire rope end terminations. One of the objectives of this R&D effort was to remedy this situation, and to develop instrumentation and a procedure for the inspection of wire rope end sections.

As part of the present SBIR Phase II research, we implemented prototype instrumentation for the inspection of wire rope end terminations. We designed, manufactured and evaluated an "end section coil" which can be attached to a regular instrument as shown in Figure 28. A photograph of the prototype end section coil arrangement is shown in Figure 29. This arrangement has the advantage that the inspection instrument can be used for regular inspections and, in combination with the end coil attachment, for end section inspections.

Close to the end termination, the socket grossly distorts the magnetic field. As expected, experiments indicated that the greatly distorted magnetic field close to the rope termination socket can conceal the relatively small distortions of the magnetic field caused by defects. The minute defect signals, superimposed on the signals caused by the distorted field, are hard to identify and evaluate.

Because of this problem, the determination of defects ultimately has to be based on a comparison of subsequent inspection results, and a basic inspection program of the following type should be implemented:

1. To establish baseline data for subsequent inspections, the program has to be initiated by a first inspection of the new rope including end termination after its installation and after a sufficient break-in period. This baseline inspection yields the "***Reference Signal.***" Note that the acquisition of separate Reference Signals for each individual rope termination is probably not necessary. A single Reference Signal, useful for all rope terminations of identical design, should be sufficient.

2. Successive periodic inspections are performed at predetermined intervals. These inspections yield the "***Test Signal.***"

3. All inspection results are compared with the results of the baseline inspection. Defects will be indicated by deviations of the ***Test Signal*** from the ***Reference Signal.***

Since the magnetic field in the rope is drastically distorted by the rope termination, defects are indicated by relatively minuscule deviations of the ***Test Signal*** from the ***Reference Signal.*** Therefore, to allow a reliable and accurate comparison of successive test results, the following two conditions have to be satisfied by the test instrumentation:

1. Test results must be reproducible with extraordinary accuracy and reliability, and

2. the comparison of test results has to be performed with great accuracy and resolution.

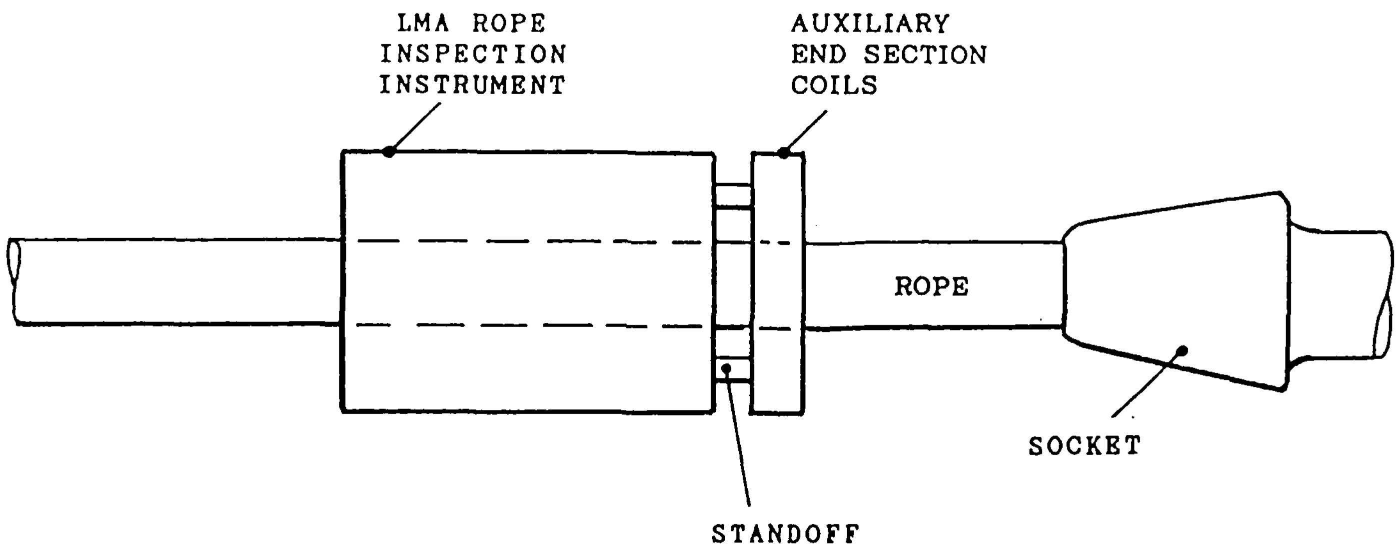


Figure 28: Instrument for the Inspection of Wire Rope End Sections

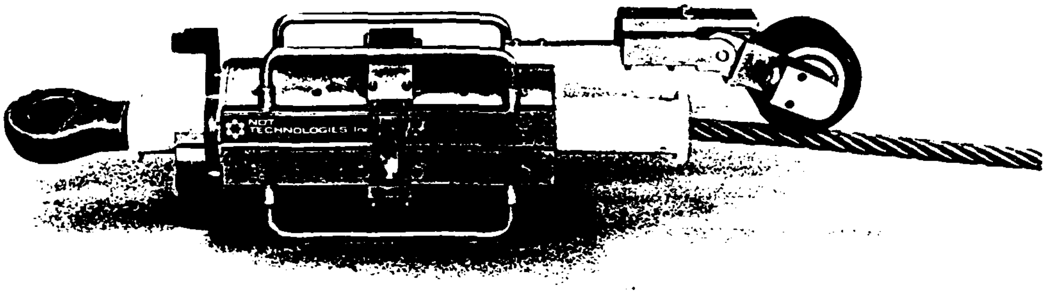


Figure 29: End Section Sense Head

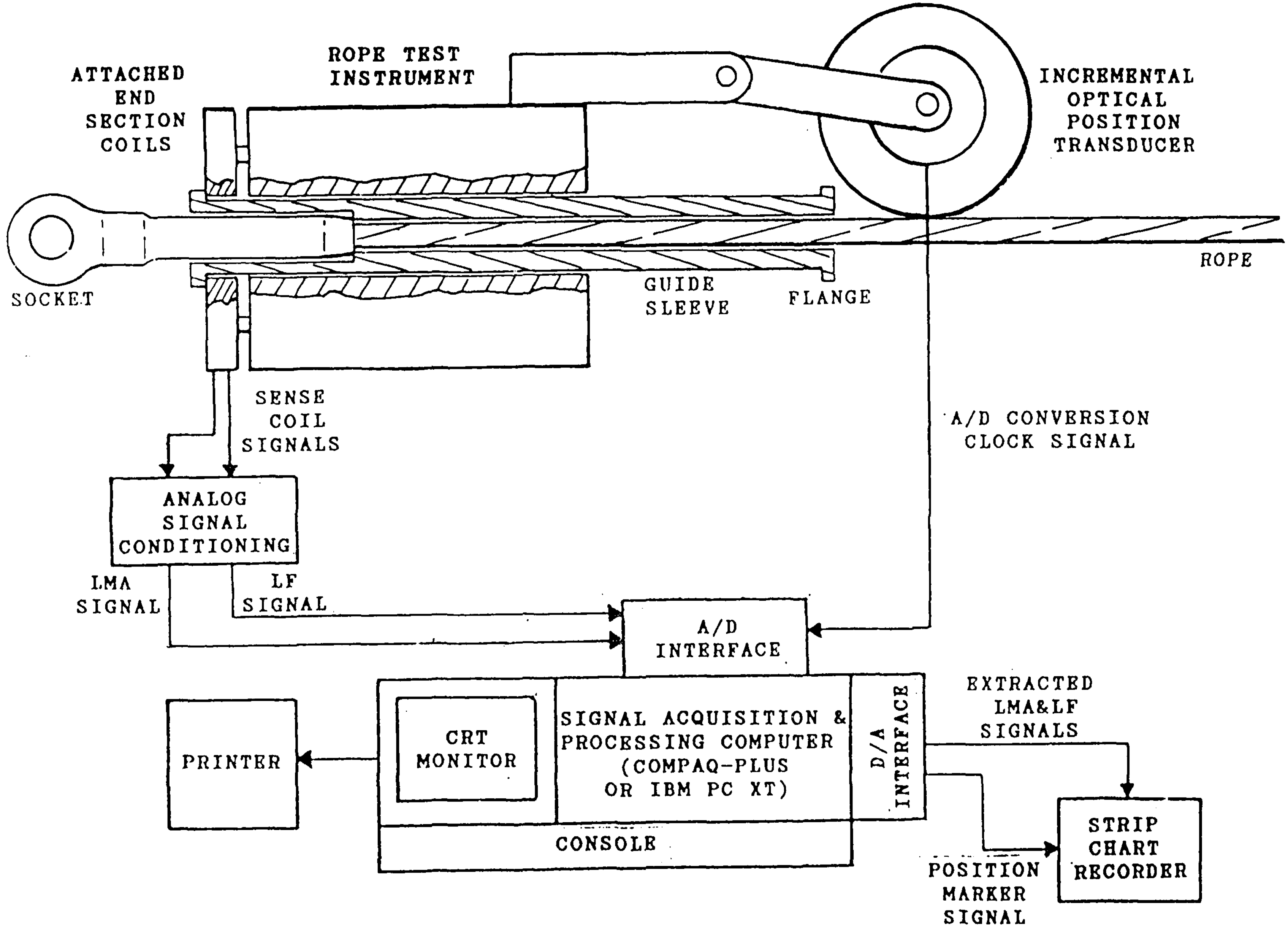


Figure 30: End Section Inspection System

In particular, to make test results reproducible, the following conditions must be satisfied:

- **Test results must be completely independent of the azimuthal position of the instrument with respect to the rope.**

  Because the magnetizer assembly as well as the attached end section coils have almost perfect rotational symmetry, this condition is satisfied for our bigger prototype instruments.

  Note that rotational symmetry is hard to achieve for instruments which use discrete sensors, such as Hall Generators or Flux Gate Sensors, for magnetic field sensing.

- **Test signal amplitudes must be independent of rope speed.**

  Because our sensor design uses sense coils together with signal integration, this condition is automatically satisfied for both, the LMA and the LF signal.

- **The position of the test signal with respect to the rope longitudinal axis must be determined with great accuracy and resolution.**

  Our incremental optical encoder was modified to allow position sensing with a resolution of approximately 0.047". This resolution is sufficient to achieve the required repeatability of the test results.

- **The magnetic state of the rope including the socket, prior to the test, must be accurately reproducible to avoid a distortion of the defect signal due to the remagnetization effect.**

  Problems caused by remagnetization of the rope can be avoided by magnetically homogenizing the rope before the inspection. Homogenization is achieved by simply moving the rope through the instrument once before the inspection.

  The socket, which is made from steel, could also become permanently magnetized in a random fashion. Although, in our lab experiments, we were not able to produce any artificial random magnetization of the socket which produced deterioration of the test results, problems of this type are conceivable.

To allow an accurate comparison of test results obtained from different inspections, our data acquisition system, comprising an IBM PC XT computer including analog/digital interface circuitry, is well suited. Figure 30 shows a functional block diagram of the arrangement which was used for our lab experiments. The following procedure was used:

1. To keep the rope and socket in a centered position with respect to the instrument, the following mechanical arrangement is used:

   A guide sleeve made from UHMW polyethylene is first mounted on the rope and on the socket as indicated in Figure 30. For easy

mounting in the field, the guide sleeve is subdivided. The instrument, with the end section coil and position transducer (incremental encoder) attached, is then mounted on the guide sleeve and the rope as shown in Figure 30, with the end section coil facing toward the rope socket. The instrument assembly can be moved in the longitudinal direction on the rope. Note that the sleeve is tightly fit to the socket in such a fashion that, as the instrument assembly moves away from the socket, the sleeve first stays stationary with respect to the socket. The magnetizer including the sense coil first moves on the guide sleeve until it reaches the flange of the guide sleeve. Then the guide sleeve moves with the instrument assembly over the rope in the longitudinal direction.

2. To magnetically homogenize the rope, the instrument is moved toward the socket and beyond the end of the socket as far as possible. Note that the inner coil diameter and the inner magnetizer diameter are larger than the diameter of the socket, and the end section coil can be moved approximately 6" beyond the end of the socket. To magnetically homogenize the rope including the socket, the instrument is moved approximately 6 feet away from the socket and is then returned to its original position on the socket. The rope including the socket is now magnetically homogenized and in a well defined magnetic state.

3. The data acquisition system is set up and programmed in such a fashion that the sampling of data points is clocked by pulses from the incremental encoder at a sampling rate of approximately 21 samples/inch. This approach, together with the previously discussed procedures, makes data acquisition independent of time and completely reproducible.

4. The computer data acquisition program is now started.

5. The instrument is manually moved away from the rope socket. As the instrument moves, the incremental encoder produces pulses at a rate of approximately 21 pulses/inch. Each pulse triggers sampling of one data point. The sampled test data points are stored on hard disk.

6. To initiate the lab experiments, an inspection of the sample rope, including socket, in its original condition is performed. These inspection results are stored on disk and serve as the ***Reference Signal***.

7. Defects are simulated by attaching short pieces of wire to the rope. Then, to obtain the ***Test Signal***, the above test procedure is repeated for the rope with these simulated rope flaws. The ***Test Signal*** is stored in the computer on hard disk.

8. A separate computer program compares the ***Reference Signal*** with the ***Test Signal***. Since both signals are reproducible with considerable accuracy and resolution, this can be accomplished by simply subtracting corresponding stored data points of the two signals.

5.3 Test Results

Figure 31 shows test results obtained from an end section inspection of a 3/4" IWRC rope using an LMA-175 instrument including an end section coil and an incremental optical encoder. The experiment was performed according to the above procedure.

The ***Reference Signal*** was acquired and stored on disk by inspecting the rope close to the end section in its original condition. To simulate a rope flaw, an 8 inch long wire with a metallic cross-sectional area of approximately 1.2% of the total rope cross-sectional area was attached to the rope with one wire end tucked under the socket for approximately 1". With this wire attached, the rope was then inspected and the ***Test Signal*** was also stored on disk. The location of the attached wire is indicated in the figure.

The upper part of Figure 31 shows the ***Reference Signal*** and the ***Test Signal.*** Caused by the socket and the rope end, the ***Reference*** and ***Test Signals*** are greatly distorted. Note that, within the resolution of the computer printout, the ***Reference Signal*** and ***Test Signal*** are almost indistinguishable.

Using the computer, the flaw signal was then extracted from both signals by subtracting the ***Reference Signal*** from the ***Test Signal.*** The extracted flaw signal is shown in the lower part of Figure 31.

Close to the rope terminations, even small deviations of the relative position of the two signals can cause drastic inaccuracies in the extracted flaw signal. Therefore, the computer program allows for a micro-adjustment of the absolute position of both signals by plus or minus one sample point (equivalent to a distance of +-0.047 inches). The adjustment is accomplished by interpolation. At this stage of the research, the position micro-adjustment is performed automatically by a simple computer optimization algorithm.

In Figure 31, the LMA signal is slightly deformed as compared to the shape of the LMA signal caused by the same flaw in an instrument with our regular symmetrical sensor-magnetizer arrangement. A computer simulation shows this deformation to be caused by the unsymmetrical coil-magnetizer geometry. Since the phenomenon is well understood, a computer algorithm could conceivably be designed to eliminate this distortion.

From this example we can draw the following conclusion: A 1.2% cross-sectional area change can be clearly detected. Since in actual rope applications, area changes of 10% or more are of concern, the present end section inspection method offers a comfortable error safety margin, and the method appears clearly feasible.

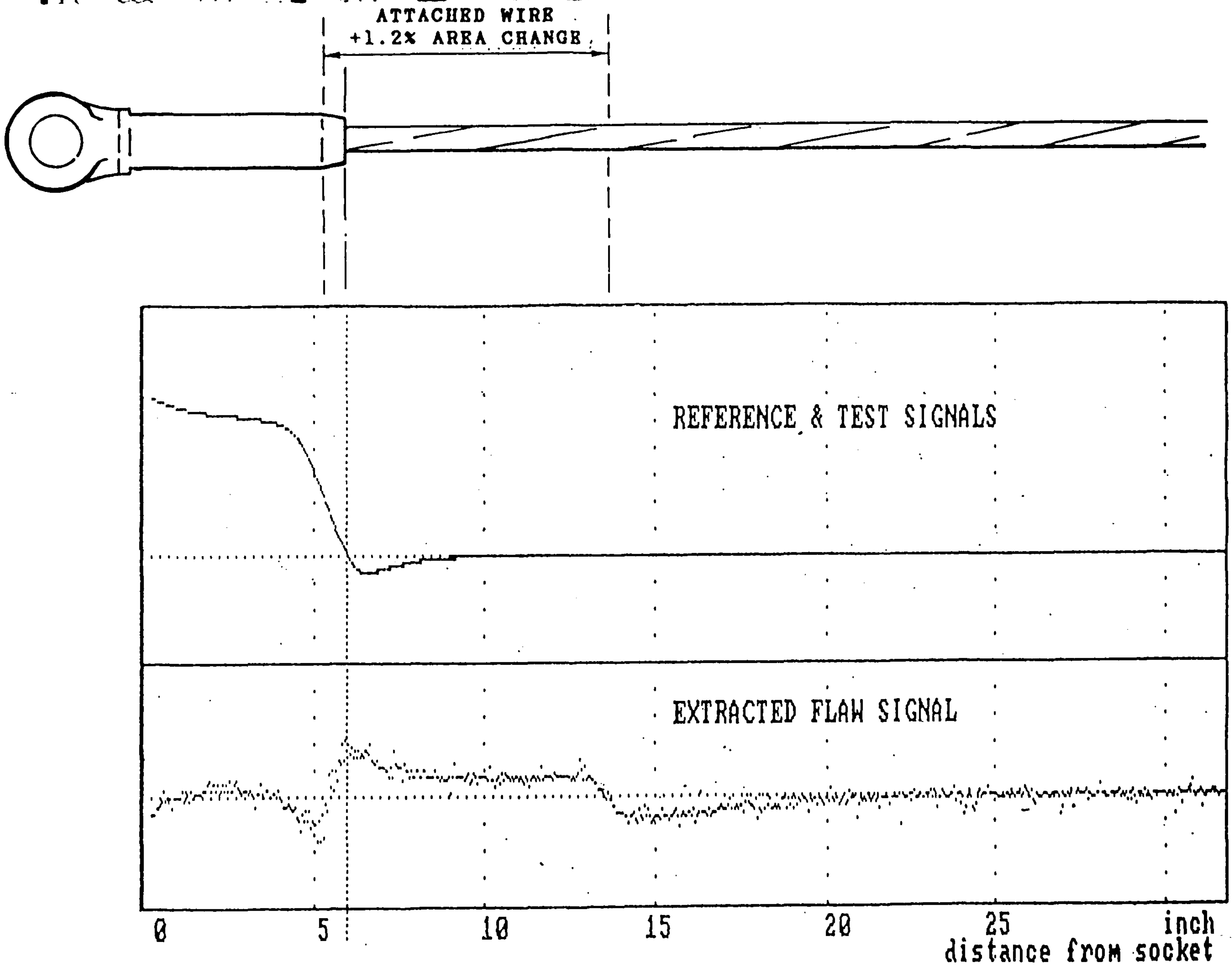


Figure 31: End Section Inspection -- Experimental Results

5.4 Data Acquisition System

For our laboratory experiments, we use an IBM PC XT Personal Computer together with Data Translation analog-digital interface hardware to implement a test system as shown in Figure 30. Unfortunately, this test set-up is not portable and therefore not suitable for field testing.

However, ruggedized portable computers, suitable for data acquisition and processing applications, are now available. They can be used, on-site, for in-service end-section inspections. An on-site data acquisition and processing computer has the advantage that test results can be immediately evaluated. Any doubts or discrepancies concerning the test results can then be directly investigated and resolved on-site.

A portable COMPAQ-Plus Personal Computer would be well suited for our data acquisition applications. This portable computer is completely equivalent to the IBM PC XT and compatible with our present Data Translation data acquisition system. The COMPAQ computer has only two minor drawbacks: It is not battery operated and requires an electrical outlet which might cause some inconvenience under certain field conditions, and, although portable and rugged, it appears primarily intended for office use. Alternate ruggedized IBM PC compatible computers, designed for military and other field applications, will undoubtedly become available in the near future. These computers can then be easily adapted for wire rope inspections.

5.5. Further Development

Although feasibility of the end section inspection method has been demonstrated by lab experiments, a considerable amount of field testing and further development will be required to make this procedure sufficiently rugged and reliable under adverse field conditions.

Field testing of our newly developed instruments has been difficult for us in the past. It is absolutely necessary because of the following reasons:

o Most of our experiments are performed in the lab under well controlled conditions. While these lab tests are indispensable for instrument development, they are often not a true reflection of instrument performance under actual and usually adverse field conditions.

Our End Section Inspection System is a completely new development, and no previous field experience with this type of inspection is available, anywhere. To make End Section Inspection, now in its infancy, a viable and accepted inspection procedure will require extensive field testing, combined with additional development work. For instance, end section inspections rely on an extremely accurate repeatability of test results. Therefore, the question of repeatability of test results under adverse field conditions is crucial and must be resolved.

To make end section inspections a viable in-service inspection procedure, the following further development work will be necessary in addition to an extensive field testing program:

<u>Development of larger instruments.</u> Since end sockets are considerably larger than the attached rope, the size of the inspection instrument has to be significantly increased for end inspections. The largest instrument presently available is useful for inspecting sockets up to 2 1/2" diameter, corresponding to rope diameters up to approximately 1". This is clearly not sufficient for inspecting all ropes presently used by the US Navy. Larger instruments, including the corresponding end section coils, would have to be designed and manufactured. Since the weight and size of instruments increases approximately as the 2.5^{th} power of the socket diameter, the design and manufacture of larger instruments poses considerable mechanical problems.

<u>Redesign optical position transducer.</u> Our present position transducer has a resolution of approximately 0.047" which is sufficient for our lab experiments. However, it would be desirable to "oversample" data points. The excess data can then be used for digital filtering which would increase testing accuracy. Therefore, a position transducer with increased resolving power should be designed and manufactured.

<u>Reconfigure signal acquisition and processing system.</u> Our present system must be reconfigured and repackaged by using a portable COMPAQ-Plus or equivalent fieldworthy computer.

<u>Redesign and extend signal conditioning software.</u> The present signal processing software is primarily intended for our lab experiments. Its operation requires considerable skill. The software should be streamlined to make it usable by less experienced personnel. The evaluation programs could be made self-prompting and menu-driven, which would make their use extremely simple.

Several automatic filter and deconvolution algorithm should be developed to make the evaluation of test results automatic and foolproof. The present optimization procedure for aligning test signals should be improved.

6. SIMPLIFIED ROPE POSITION TRANSDUCER.

We designed, manufactured and evaluated a simplified rope distance counter. The new rope distance transducers, using permanent magnets and sense coils, are drastically simpler than our previous position transducer designs which incorporate an optical encoder.

The design of the new distance counter is very simple. Small permanent ferrite magnets are embedded into the body of a rubber wheel. The rope drives the wheel. The moving magnets induce pulses in two sense coils as the wheel moves. The coils are positioned in a quadrature arrangement which, by using simple logic circuitry, allows direction sensing. The rope position is determined by counting the induced pulses in an up-down counter.

The new position transducer is drastically simpler and more rugged than our previous designs which use an optical encoder. Another advantage of the new transducer is that it uses only passive components such as permanent magnets and coils which do not require a power supply. For instance, the new transducer could easily be adapted for underwater operation.

Note, however, that the resolution of the new transducer is only approximately 0.2 inches. Therefore, for end section inspections our previous optical position transducers with their much better resolution will still be required.

7. DATA ACQUISITION TAPE RECORDER

For data acquisition in the field, a tape recorder system was developed. The system uses frequency modulation-demodulation interface circuitry for storing analog signals on commercially available cassette tape recorders. The frequency range of the system is 0 to 200Hz. Both, the LF and the LMA signal can be stored. Distance markings are stored on a third auxiliary channel. The system can be used to play the signals back to a stripchart recorder, Alternatively, the cassette recorder analog data acquisition system can also be interfaced to our digital data acquisition system for further signal processing and for defect identification.

9. AVAILABLE WIRE ROPE INSPECTION INSTRUMENTS

During the course of the present R&D effort, several wire rope inspection instruments of the LMA/LF type were developed. Completely developed and presently available are the LMA-250, LMA-175, LMA-125 and LMA-75 instruments for ropes up to 2 1/2 inches, 1 3/4 inches, 1 1/4 inches and 3/4 inches, respectively.

Here is a brief description of this new instrumentation:

APPLICATION: The Rope Testers of the LMA-Test series are used in the field to test for and measure loss of metallic cross-sectional area (LMA) caused by external and internal corrosion, abrasion, broken wires, broken cores and deformations in steel wire ropes. In addition, a localized-flaw (LF) signal is available which can be used to pinpoint the location of a wide variety of flaws, such as broken wires and corrosion pitting. Rope Testers of the LMA-Test series were developed as an accurate diagnostic tool for thorough rope inspections. In addition, the instruments are well suited for simple routine testing of wire ropes in military, mining and industrial applications where safety and hence the detection of wire rope anomalies is of paramount importance.

OPERATION: A section of the steel rope is magnetically saturated in the longitudinal direction by strong permanent magnets. Discontinuities in the rope such as a broken wire, a broken core, corrosion or abrasion distort the longitudinal magnetic flux, and flux leaks from the rope into the surrounding air space. Sensors, close to the rope, sense the leakage flux. The rope moves which causes the leakage flux to intersect the sensors. The changing

intersecting flux induces signals in the sensors. Electronic circuitry conditions and modifies the signals. A strip chart recorder, a buzzer, and a flaw counter display the signals visually and aurally.

DESCRIPTION: The Sense Head Assembly, Signal Console, Strip Chart Recorder, Cassette Tape Recorder, and other accessories are stored in two Carrying Cases.

Two different types of signals are available:

(i) The **LOSS-OF-METALLIC-AREA (LMA) SIGNAL** gives a quantitative measure of the loss of metallic cross-sectional area of the rope caused by corrosion, abrasion, broken wires, etc.

(ii) The **LOCALIZED-FLAW (LF) SIGNAL** can pinpoint the location of a wide variety of flaws, such as broken wires and corrosion pitting. An audio display of this signal, useful for a simplified inspection, is available. After flaws have been located by using the LF signal, their actual nature can be ascertained by analyzing the corresponding section of the LMA signal and/or by an audio-visual rope inspection.

In operation, the Sense Head attaches to the rope by means of rope guides to detect flaws as the rope moves at rates from 5 fpm to high speeds of 600 fpm. The fault signals are recorded by a strip chart recorder and/or a cassette recorder. Different rope flaws are then identified from their characteristic chart patterns. In addition, localized rope flaws are indicated by beeps of the built-in Buzzer and can be counted by a Flaw Counter.

A Rope Distance Counter indicates length and speed of the rope tested. Distance marker signals on the test chart indicate every 10 ft, with emphasis on every 100 ft, of the rope under test.

Specifications for the available wire rope inspection instruments are given on the following pages.

LMA-250 WIRE ROPE INSPECTION SYSTEM

This instrument can inspect wire ropes with 3/8"- 2 1/2" (9 - 64 mm) diameters. At a weight of only 57 lb, the LMA-250 sense head is approximately 40% lighter than the sense head of competing instruments. The LMA-250 System comes with a rope velocity and position sensor; a strip chart recorder is included. A cassette tape recorder is optional.

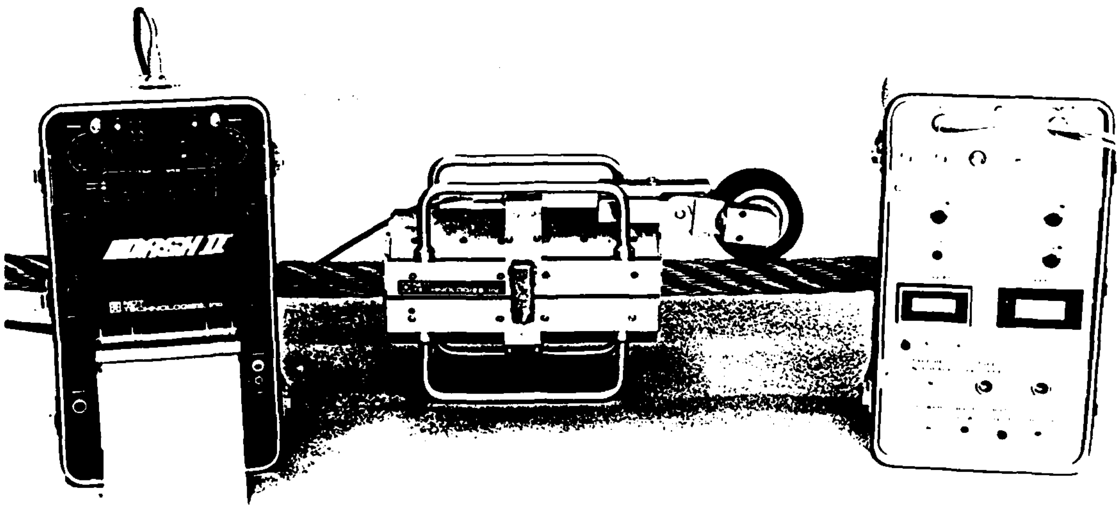


Figure 32: LMA-250 Wire Rope Tester

Sensor Head

Dimensions (LxWxH)....................11" x 7" x 9"

Weight ....57 lbs.

Signal Console

Dimensions (LxWxH)....................13" x 8" x 9"

Weight ....9 lbs

Batteries ....Rechargeable NiCad batteries. 12 hours of continuous operation. Battery charger. Low voltage indicator. LED indicator turns on at end of battery life. Push button to check battery condition.

Performance

Rope Sizes............................Up to 2 1/2" diameter

Rope Speed............................0 to 600 feet per minute

Test Signals..........................LF and LMA signal, amplitudes independent of rope speed.

Flaw Detection........................Loss of metallic cross-sectional area (LMA): external and internal broken wires, corrosion, abrasion, broken cores, various changes of rope structure. Localized flaws (LF): broken wires, corrosion pitting.

Flaw Detectability....................Flaw cross section: .05% of rope cross-sectional area. Quantitative flaw identification of loss of metallic cross-sectional area for flaws longer than 2", qualitative flaw identification for localized flaws.

Environmental Conditions.............Dust proof, splash proof (oil and water), humidity to 95%. Operating temperature: 0 degree to 55 degree C. Storage temperature: -40 degree to 55 degree C.

<u>Readout and Recording</u>

Rope Distance Counter................Digital panel readout. Event markers indicating every 10 ft, and emphasizing every 100 ft of rope inspected.

Flaw Counter.........................Digital panel readout. Counts broken wires. Corrosion pitting indicated by rapidly increasing count.

Strip Chart Recorder.................Two channel recorder. Rope flaws indicated by characteristic chart patterns. Signal amplitudes independent of rope speed. Event markers indicating every 10 ft, emphasizing every 100 ft of rope inspected.

Cassette Tape Recorder...............Portable stereo cassette recorder. FM interface circuitry. Records LMA and LF signals plus rope distance pulses. Playback to Strip Chart Recorder or Digital Computer.

Buzzer...............................Localized Flaws indicated by buzzer signal.

LMA-175 WIRE ROPE INSPECTION SYSTEM

This LMA.Tester is suitable for testing wire ropes up to 1 3/4" (45 mm) diameter. The light weight of its test head of only 32 lb and its design for easy handling makes the LMA-175 Tester especially useful for applications in the aerial tramway industry where ropes also have to be inspected over towers and slack rope carriers. A rope position and velocity sensor, a strip chart recorder and a cassette tape recorder for this instrument are available.

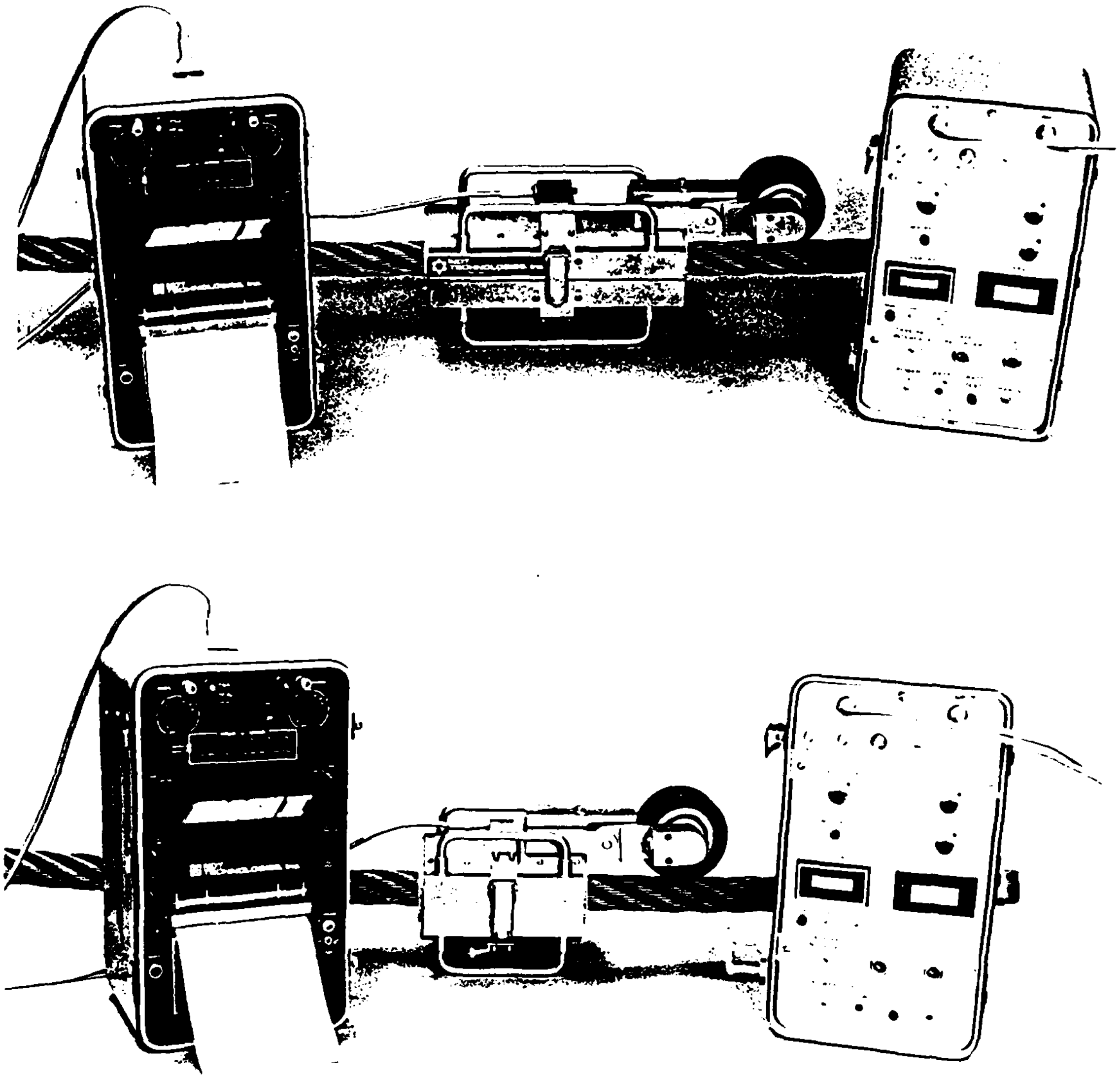


Figure 33: LMA-175 Wire Rope Tester

Sensor Head

Dimensions (LxWxH)....................11" x 6" x 7"

Weight ....32 lbs.

Signal Console

Dimensions (LxWxH)....................13" x 8" x 9"

Weight ....9 lbs

Batteries ....Rechargeable NiCad batteries. 12 hours of continuous operation. Battery charger. Low voltage indicator. LED indicator turns on at end of battery life. Push button to check battery condition.

Performance

Rope Sizes............................Up to 1 3/4" diameter

Rope Speed............................0 to 600 feet per minute

Test Signals..........................LF and LMA signal, amplitudes independent of rope speed

Flaw Detection........................Loss of metallic cross-sectional area (LMA): external and internal broken wires, corrosion, abrasion, broken cores, various changes of rope structure. Localized flaws (LF): broken wires, corrosion pitting.

Flaw Detectability....................Flaw cross section: .05% of rope cross-sectional area. Quantitative flaw identification of loss of metallic cross-sectional area, qualitative flaw identification for localized flaws.

Environmental Conditions	**Dust proof, splash proof (oil and water), humidity to 95%. Operating temperature: 0 degree to 55 degree C. Storage temperature: -40 degree to 55 degree C.**

Readout and Recording

Rope Distance Counter	Digital panel readout. Event markers indicating every 10 ft, and emphasizing every 100 ft of rope inspected.
Flaw Counter	Digital panel readout. Counts broken wires. Corrosion pitting indicated by rapidly increasing count.
Strip Chart Recorder	Two channel recorder. Rope flaws indicated by characteristic chart patterns. Signal amplitudes independent of rope speed. Event markers indicating every 10 ft, *emphasizing* every 100 ft of rope inspected.
Cassette Tape Recorder	Portable stereo cassette recorder. FM interface circuitry. Records LMA and LF signals plus rope distance pulses. Playback to Strip Chart Recorder or Digital Computer.
Buzzer	Localized Flaws indicated by buzzer signal.

LMA-125 WIRE ROPE INSPECTION SYSTEM

This LMA-Tester is suitable for testing wire ropes up to 1 1/4" (32mm) diameter. Its light weight of only 19 lb and its ease of handling make this instrument useful for a wide variety of diagnostic and routine inspections for military and industrial applications. A rope distance counter is included. A strip chart recorder and a cassette tape recorder are optional items.

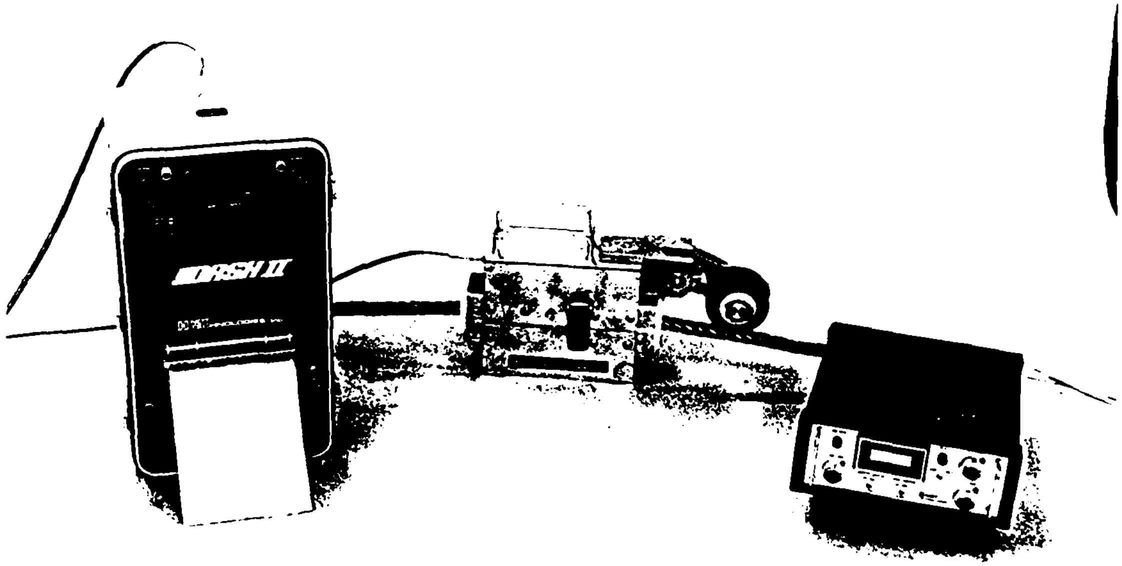


Figure 34: LMA-125 Wire Rope Tester

Sensor Head

Dimensions (LxWxH)....................11" x 2.5" x 7.5"

Weight ....19 lbs.

Signal Console

Dimensions (LxWxH)....................12" x 8.5" x 3.5"

Weight ....5 lbs

Batteries ....Rechargeable NiCad batteries. 12 hours of continuous operation. Battery charger. Low voltage indicator. LED indicator turns on at end of battery life. Push button to check battery condition.

Performance

Rope Sizes............................Up to 1 1/4" diameter

Rope Speed............................0 to 600 feet per minute

Test Signals..........................LF and LMA signal, amplitudes independent of rope speed

Flaw Detection........................Loss of metallic cross-sectional area (LMA): external and internal broken wires, corrosion, abrasion, broken cores, various changes of rope structure. Localized flaws (LF): broken wires, corrosion pitting.

Flaw Detectability....................Flaw cross section: .1% of rope cross-sectional area. Quantitative flaw identification for flaws longer than 2", qualitative flaw identification for flaws shorter than 2".

Environmental Conditions	**Dust proof, splash proof (oil and water), humidity to 95%.** Operating temperature: 0 degree to 55 degree C. Storage temperature: -40 degree to 55 degree C.

<u>Readout and Recording</u>

Rope Distance Counter (Flaw Counter)	Digital panel readout. Up-down counter indicating exact position (in feet) of instrument on rope under test. Alternatively, the digital panel readout can be used as a flaw counter.
Strip Chart Recorder (optional)	Two channel recorder. Rope flaws indicated by characteristic chart patterns. Signal amplitudes independent of rope speed. Event markers indicating every 10 ft, emphasizing every 100 ft of rope inspected. **Alternatively, the event markers can be used to indicate the position of flaws on strip chart recordings.**
Cassette Tape Recorder (optional)	Portable stereo cassette recorder. FM interface circuitry. Records LMA and LF signals plus rope distance pulses. Playback to Strip Chart Recorder or Digital Computer.
Buzzer	Localized Flaws indicated by buzzer signal.

LMA-75 WIRE ROPE INSPECTION SYSTEM

Significantly smaller and much less expensive than other instruments with similar performance, the LMA-75 Rope Tester is a full-fledged "loss-of-metallic-area" instrument with superior performance. Hand-held, it is suitable for inspecting ropes up to 3/4" (19 mm) diameter. A rope position and velocity sensor for this rope tester, a strip chart recorder and a cassette tape recorder are available. A strand/lay counter for this instrument will be available shortly. The LMA-75 is the only "loss-of-metallic-area" instrument presently available for inspecting tightly spaced elevator ropes.

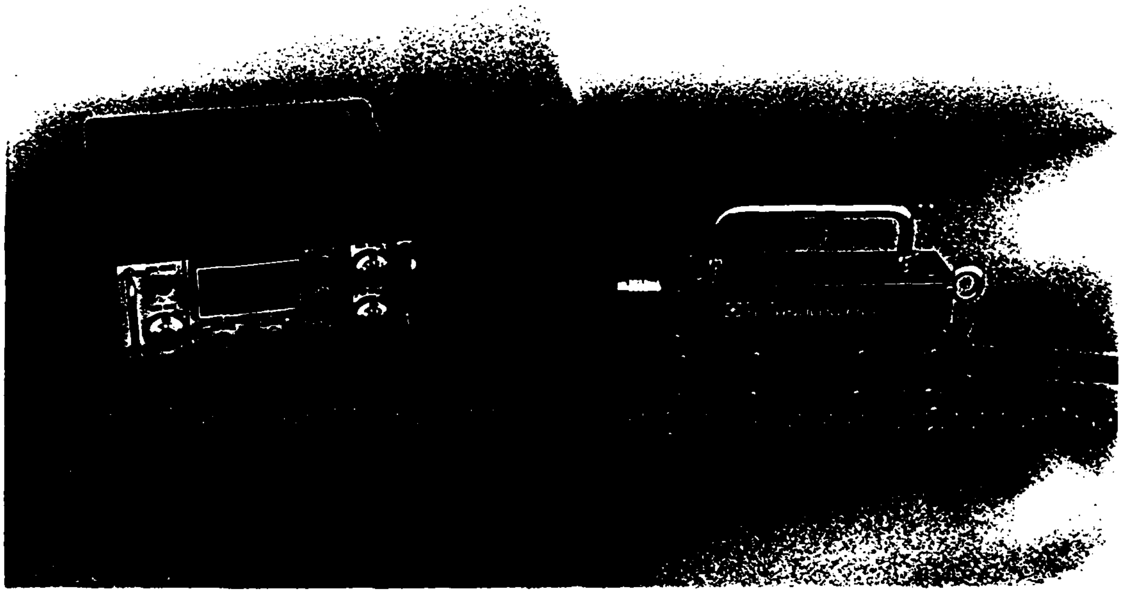


Figure 35: LMA-75 Wire Rope Tester

<u>Sensor Head</u>

Dimensions (LxWxH)....................8" x 1 1/2" x 4 3/8"

Weight ....6 lbs.

<u>Signal Console</u>

Dimensions (LxWxH)....................6" x 3" x 9"

Weight ....2 lbs

Batteries ....Rechargeable NiCad batteries. 12 hours of continuous operation. Battery charger. Low voltage indicator.
LED indicator turns on at end of battery life.
Push button to check battery condition.

<u>Performance</u>

Rope Sizes............................Up to 3/4" diameter

Rope Speed............................0 to 600 feet per minute

Test Signals..........................Amplitudes independent of rope speed

Flaw Detection........................Loss of metallic cross-sectional area (LMA):
External and internal broken wires, corrosion, abrasion, broken cores, various changes of rope structure.
Localized flaws (LF):
broken wires, corrosion pitting.

Flaw Detectability....................Flaw cross section:
.05% of rope cross-sectional area.
Quantitative and qualitative flaw identification.

Environmental Conditions............Dust proof, splash proof (oil and water), humidity to 95%. Operating temperature: 0 degree to 55 degree C. Storage temperature: -40 degree to 55 degree C.

Readout and Recording

Strip Chart Recorder.................Optional (at extra cost). One or two channel recorder. Rope flaws indicated by characteristic chart patterns. Signal amplitudes independent of rope speed. Rope Flaws highlighted by event marker.

Buzzer..............................Flaws indicated by buzzer signal Indication independent of rope speed.

Broken Wire Counter..................counts total number of localized rope flaws. Liquid Crystal Readout.

Rope Distance Indicator..............Optional (at extra cost). Digital LCD readout. Event markers on stripchart recordings indicating every 10 ft and highlighting every 100 ft of rope length.

Magnetic Cassette Tape Recorder......Optional (at extra cost). Two channel data acquisition magnetic cassette tape recorder. Additional auxiliary channel for rope distance recording.

9. SUMMARY AND CONCLUSION

Present visual methods for the inspection of wire ropes have serious deficiencies and cannot identify unsafe wire ropes which should be replaced. Furthermore, visual inspection methods are wasteful because they usually cannot identify wire ropes that have additional safe service life left.

Electromagnetic methods for nondestructive testing of wire ropes are much more reliable than purely visual methods. Nondestructive test instruments are now available which can reliably test wire ropes in service and which can remedy the shortcomings of visual wire rope inspection methods.

Two different and distinct types of nondestructive inspection methods have evolved: (i) Localized Fault (LF) Inspection for the qualitative detection of localized flaws such as external and internal broken wires, corrosion pitting, and mechanical damage. (ii) Inspection for Loss of Metallic Cross-Sectional Area (LMA) for the detection and quantitative evaluation of distributed flaws such as external and internal abrasion and corrosion.

Modern rope inspection instruments allow a simultaneous LMA/LF inspection. These instruments use DC magnetization of the rope, usually by permanent magnets. When the rope is magnetically saturated, the longitudinal magnetic flux in the rope is proportional to the rope's metallic cross-sectional area. Therefore, any loss of metallic area can be determined by measuring the longitudinal magnetic flux in the rope.

Two different classes of LMA/LF instruments are presently available: *main flux* and *return flux* instruments. *Main flux* instruments measure the flux in the rope directly which allows a very accurate cross-sectional area determination. *Return flux* instruments obtain an estimate of the longitudinal flux in the rope by measuring some flux density outside the rope. An estimate of the longitudinal rope flux is then derived from this external flux density measurement.

While all modern LMA/LF instruments offer greatly improved testing reliability as compared to the previous state of the art, *main flux* instruments have superior resolving power which makes data interpretation easy and very reliable.

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